Effects of reducing dietary crude protein levels and replacement with crystalline amino acids on growth performance, carcass composition, and fresh pork quality of finishing pigs fed ractopamine hydrochloride

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ABSTRACT: Progeny of GPK-35 females mated to PIC 380 boars were blocked by initial BW, and within the 9 blocks, pens of pigs (3 gilts and 3 barrows/pen) were randomly assigned to dietary treatments where CP of finisher-I, -II, and -III diets was 1) 16.04, 14.55, and 16.23%, respectively (Ctrl); 2) 14.76, 13.48, and 15.27%, respectively (ILE); 3) 14.26, 12.78, and 14.28%, respectively (VAL); or 4) 12.65, 12.38, and 13.32%, respectively (NoSBM). All finisher-III diets included 10 mg/kg of ractopamine hydrochloride (RAC) and a Lys:ME ratio of 2.79 g/Mcal. At slaughter, HCW and Fat-O-Meat^{er} data were recorded before carcasses were subjected to a rapid chilling process. A subsample of whole hams (2/pen) and whole loins (2/pen) were transported under refrigeration to the University of Arkansas. Hams were dissected with a knife into lean, fat, and bone, and 2.5-cm-thick chops from the semimembranosus (SM) and the LM were used to measure fresh pork quality characteristics. Both ADG and G:F decreased (linear, $P = 0.05$) as CP decreased in finisher-I diets, whereas ADFI was reduced (linear, $P = 0.01$) in response to decreasing CP in finisher-II diets. When RAC was included in the

finisher-III diets, ADFI and BW decreased (linear, $P \leq 0.03$) with decreasing CP, and pigs fed the ILE diet had greater (cubic, $P < 0.01$) G:F than pigs fed the Ctrl and VAL diets. Across the entire finishing period, ADG and ADFI decreased (linear, $P = 0.01$) in response to reductions in dietary CP. Conversely, reducing CP in finisher diets did not ($P \geq 0.13$) affect carcass yield, fat depth, LM depth, or calculated fat-free lean yield, and dietary CP content did not ($P \geq 0.09$) alter the lean, fat, or bone composition of fresh hams. Moreover, there was no effect of dietary CP on the visual and instrumental color or firmness of the LM ($P \geq 0.06$) or SM ($P \geq 0.12$). However, there were linear increases in LM marbling scores ($P = 0.02$) and intramuscular fat content ($P = 0.03$) as CP was reduced in the finisher diets. Although reducing dietary CP decreased overall ADG and ADFI by approximately 6.1 and 4.9%, respectively, carcass composition was not impacted by dietary CP level. More importantly, reducing dietary CP, although meeting the standard ileal digestible requirements for Lys, Thr, Trp, Met, Ile, and Val with crystalline AA, did not impact pork color or water-holding capacity and actually increased the intramuscular fat content of the LM.

Key words: carcass composition, crude protein level, growth performance, pork quality, ractopamine hydrochloride, swine

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INTRODUCTION

Nitrogen compounds from manure and urine are oxidized/reduced by soil and air, with some nitrogen being released into the atmosphere as nitrous oxide (N₂O). The greenhouse warming power of N₂O is about 288

times that of CO₂ (Ravishankara et al., 2009; Shcherbak et al., 2014); therefore, N₂O has the next largest impact on the climate after CO₂ and methane. Maximizing crystalline AA use and reducing dietary CP in swine diets reduces nitrogen excretion in both nursery and growing/finishing swine (Kerr and Easter, 1995; Hayes et al., 2004; Atakora et al., 2011); however, there has been variability in growth performance and carcass characteristics when reduced-CP diets were fed (Kerr et al., 1995; Canh et al., 1998; Figueroa et al., 2002). Moreover, even though preliminary studies indicate that

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pigs could be fed lower-CP diets with appropriate added AA and containing ractopamine hydrochloride (**RAC**) without compromising performance or carcass composition (DeCamp et al., 2001; Gaines et al., 2004), U.S. Food and Drug Administration regulations still require that RAC diets contain 16% CP (Feed Additive Compendium, 2010). These studies suggest that the maximum level of CP reduction, in conjunction with the optimum AA inclusion rate, has not been sufficiently determined for widespread acceptance by the swine industry.

Reducing the CP content of grower and finisher diets has been repeatedly shown to increase intramuscular fat (**IMF**) content between 14 and 65% (Kerr et al., 1995; Teye et al., 2006). Yet the reductions in IMF content or marbling anecdotally associated with feeding RAC are more than likely a response to dietary Lys levels in excess of 0.8% (Apple et al., 2007). Therefore, the objective of this experiment was to determine the impact of sequential increases in crystalline AA in reduced-CP diets on growth performance, carcass composition, and fresh pork quality of finishing pigs fed RAC.

MATERIALS AND METHODS

All protocols and procedures were approved by the University of Arkansas Interdepartmental Animal Care and Use Committee (protocol number 10041) before initiating the experiment.

Animals and Diets

A total of 216 crossbred pigs, from the mating of GPK-35 females (Newsham Genetics, Inc., St. Louis, MO) to line-380 boars (PIC, Inc., Hendersonville, TN), were blocked by initial BW into 9 blocks. Within each block, pens of pigs (3 barrows and 3 gilts per pen) were randomly assigned to 1 of 4 dietary treatments (Table 1) when pigs weighed approximately 62.0 kg: 1) corn-soybean meal-based finisher-I, -II, and -III diets containing 16.04, 14.55, and 16.23% CP, respectively (**Ctrl**), and formulated to meet the standard ileal digestible (**SID**) ideal AA requirements for Thr, Met, and Trp with synthetic, crystalline AA (Evonik Corp., Parsippany, NJ); 2) corn-soybean meal-based finisher-I, -II, and -III diets containing 14.76, 13.48, and 15.27% CP, respectively, and formulated to meet SID ideal AA requirements for Lys, Thr, Met, and Trp with synthetic, crystalline AA (Evonik Corp.) and minimum SID Ile (**ILE**) requirements without supplemental crystalline Ile; 3) corn-soybean meal-based finisher-I, -II, and -III diets containing 14.26, 12.78, and 14.28% CP, respectively, and formulated to meet SID ideal AA requirements for Lys, Thr, Trp, Met, and Ile with synthetic, crystalline AA (Evonik Corp.) and the minimum SID requirements for Val (**VAL**) without

supplemental crystalline Val; or 4) corn-based finisher-I, -II, and -III diets (finisher-I and -II diets were devoid of soybean meal, whereas 10.5% soybean meal was included in the finisher-III diet) containing 12.65, 12.38, and 13.32% CP, respectively (**NoSBM**), and formulated to SID requirements for Lys, Thr, Trp, Met, Ile, and Val with synthetic AA (Evonik Corp.). The actual AA composition of finisher diets is presented in Table 2.

Pigs were housed in a curtain-sided building with slatted floors, and each 1.49- by 3.96-m pen was equipped with a single-opening feeder and nipple waterer, which afforded each pig ad libitum access to both feed and water. Pigs were fed a 5-phase dietary program, with transition from grower-I to grower-II, grower-II to finisher-I, finisher-I to finisher-II, and finisher-II to finisher-III diets at mean block weights of 50.0, 62.0, 84.0, and 100.0 kg, respectively. It should be noted that all pigs were fed the same corn-soybean meal-based diets that met or exceeded NRC (1998) requirements during the 2 grower phases. Moreover, RAC (Elanco Animal Health, Greenfield, IN) was included in all finisher-III diets at 10 mg/kg, and these diets were formulated with incremental 0.15% levels of crystalline Lys to achieve a total SID Lys content of 0.954% and a constant Lys:ME ratio of 2.79 g Lys/Mcal (Apple et al., 2004). Individual pig weights and feed disappearance were recorded weekly to calculate ADG, ADFI, and G:F.

Carcass Data Collection

When the average BW of 127.0 kg was achieved, all pigs were individually weighed and transported approximately 10 h to a commercial pork slaughter/fabrication facility (Cargill Meat Solutions, Beardstown, IL), where pigs were stunned with CO₂ and slaughtered according to humane, industry-accepted procedures after a 6-h lairage. Fat and LM depths were measured in the area of the 10th rib with a Fat-O-Meat'er probe (Carometec Inc., Peosta, IA), and HCW was recorded before carcasses were exposed to a 24-h rapid chilling system (90 min at -20°C, with a gradual increase in temperature from approximately -4 to 1°C thereafter). Approximately 4.5 h after exiting the blast chiller, left-side hams (1 barrow and 1 gilt/pen) and loins (1 barrow and 1 gilt/pen) were individually identified. Then, identified whole, bone-in hams and whole, bone-in loins were collected during carcass fabrication (24 h after stunning), packaged, boxed, and transported under refrigeration to the University of Arkansas Red Meat Research Abattoir (Fayetteville, AR) for additional data collection.

Ham Fabrication. Upon arrival, pH was measured in the center of the semimembranosus (**SM**) of each ham with a hand-held, ceramic-tipped, temperature-compensating pH probe (205 pH/Temperature Meter; Testo, Inc.,

Table 1. Diet composition (as-fed basis)¹

	Finisher-I (62 to 84 kg)				Finisher-II (84 to 100 kg)				Finisher-III (100 to 132 kg) ²			
	Ctrl	ILE	VAL	NoSBM	Ctrl	ILE	VAL	NoSBM	Ctrl	ILE	VAL	NoSBM
Formulated CP, %	16.04	14.76	14.26	12.65	14.55	13.48	12.78	12.38	16.23	15.27	14.28	13.32
Ingredient, %												
Corn	65.66	69.07	70.41	74.79	69.54	72.40	74.28	75.37	75.36	78.09	80.90	83.64
Soybean meal	10.25	6.50	5.00	0.00	6.48	3.35	1.25	0.00	19.60	16.60	13.50	10.50
DDGS ³	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	—	—	—	—
Restaurant grease	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.65	1.55	1.45	1.35
Dicalcium phosphate	0.68	0.70	0.71	0.75	0.59	0.61	0.63	0.64	1.02	1.04	1.06	1.09
Limestone	0.99	1.01	1.02	1.04	0.99	1.01	1.02	1.02	0.60	0.61	0.63	0.64
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
L-Lys	0.500	0.685	0.760	1.008	0.500	0.655	0.758	0.820	0.549	0.698	0.850	0.999
D,L-Met	0.015	0.050	0.064	0.112	—	0.020	0.039	0.051	0.157	0.185	0.214	0.243
L-Thr	0.093	0.145	0.165	0.235	0.078	0.121	0.150	0.167	0.184	0.226	0.269	0.310
L-Trp	0.015	0.035	0.043	0.069	0.019	0.036	0.040	0.054	0.02	0.036	0.052	0.068
L-Ile	—	—	0.025	0.110	—	—	0.036	0.058	—	0.051	0.104	0.155
L-Val	—	—	—	0.085	—	—	—	0.020	0.008	0.059	0.113	0.164
Vitamin premix ⁴	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Mineral premix ⁵	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Tylan-40	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Ethoxiquin	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Calculated composition												
ME, Mcal/kg	3.38	3.39	3.39	3.40	3.39	3.39	3.39	3.40	3.42	3.42	3.42	3.42
SID ⁶ Lys, %	0.91	0.90	0.90	0.88	0.67	0.67	0.67	0.67	0.95	0.95	0.95	0.95
Lys:ME ratio	2.27	2.27	2.27	2.27	1.99	1.99	1.99	1.99	2.79	2.79	2.79	2.79
SID Met, %	0.27	0.28	0.29	0.31	0.23	0.24	0.25	0.25	0.38	0.40	0.41	0.43
SID Thr, %	0.54	0.54	0.54	0.54	0.47	0.47	0.47	0.47	0.76	0.76	0.75	0.74
SID Trp, %	0.13	0.13	0.13	0.13	0.11	0.11	0.11	0.11	0.19	0.19	0.19	0.19
SID Ile, %	0.49	0.43	0.43	0.43	0.43	0.38	0.38	0.38	0.64	0.63	0.62	0.62
SID Val, %	0.61	0.55	0.52	0.52	0.55	0.50	0.46	0.46	0.65	0.65	0.65	0.65
Available P, %	0.28	0.28	0.28	0.28	0.26	0.26	0.26	0.26	0.24	0.24	0.24	0.24
Total Ca, %	0.61	0.61	0.61	0.61	0.58	0.58	0.58	0.58	0.56	0.56	0.56	0.56

¹Ctrl = finisher-I, -II, and -III diets formulated with crystalline AA to meet standard ileal digestible (SID) ideal AA requirements for Thr, Met, and Trp; ILE = finisher-I, -II, and -III diets formulated to meet minimum SID Ile requirements without supplemental crystalline Ile, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Met, and Trp; VAL = finisher-I, -II, and -III diets formulated to meet minimum SID Val requirements without supplemental crystalline Val, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Trp, Met, and Ile; NoSBM = finisher-I and -II diets formulated without soybean meal (SBM) but finisher-III diet was formulated with 10.5% SBM and all diets were formulated with crystalline AA to meet SID ideal AA requirements for Lys, Thr, Trp, Met, Ile, and Val.

²10 mg/kg (0.05%, as-fed basis) ractopamine hydrochloride (Paylean; Elanco Animal Health, Greenfield, IN) was included in all diets.

³DDGS = dried distiller's grains with solubles.

⁴Premix supplied 6,614 IU vitamin A, 827 IU vitamin D₃, 26 IU vitamin E, 2.7 mg vitamin K, 16.5 mg pantothenic acid, 30 mg niacin, 5 mg riboflavin, and 26 µg vitamin B₁₂ per kilogram of feed (Nutra Blend Corp., Neosho, MO).

⁵Premix supplied 138 mg/kg Fe from ferrous sulfate, 138 mg/kg Zn from zinc sulfate, 33 mg/kg Mn as manganous sulfate, 13.8 mg/kg Cu from copper sulfate, 0.25 mg/kg Se from sodium selenite, and 0.25 mg/kg I from calcium iodate per kilogram of feed (Nutra Blend Corp.).

⁶SID = standard ileal digestible.

Sparta, NJ) calibrated to pH 4.0 and 10.0. Then, each ham was weighed and subsequently dissected with a knife into the “flat” (biceps femoris), “pillow” (SM and adductor), “knuckle” (quadriceps complex), semitendinosus, lean muscle trim, fat trim, and bone (including skin). Weights of each component were recorded, and the weights of all lean (muscles and lean muscle trim), fat, and bone were divided by the whole ham weight to calculate yields. The adductor was subsequently removed from each “pillow,” and after 3 cm of the dorsal edge of the SM was removed,

steaks were cut perpendicular to the muscle fiber orientation for visual and instrumental color, firmness, and marbling data collection (one 2.5-cm-thick steak) and drip loss determination (two 3.8-cm-thick steaks), and a 2.5-cm-thick steak was vacuum packaged and immediately frozen for Warner–Bratzler shear force (WBSF) determinations at a later date.

Loin Fabrication. As previously described, pH of the LM from each loin was recorded before the blade, tenderloin, and sirloin sections of each loin were removed.

Table 2. Actual dietary AA composition¹

Formulated CP, %	Finisher-I (62 to 84 kg)				Finisher-II (84 to 100 kg)				Finisher-III (100 to 132 kg) ²			
	Ctrl	ILE	VAL	NoSBM	Ctrl	ILE	VAL	NoSBM	Ctrl	ILE	VAL	NoSBM
Formulated CP, %	16.04	14.76	14.26	12.65	14.55	13.48	12.78	12.38	16.23	15.27	14.28	13.32
DM, %	87.81	87.92	87.95	87.93	88.63	88.51	88.25	88.04	88.28	88.33	88.33	88.28
Actual CP, %	15.66	14.15	13.87	11.87	14.83	13.14	12.81	11.96	16.14	14.79	14.17	12.99
AA, %												
Lysine	0.90	0.85	0.85	0.79	0.88	0.79	0.84	0.89	1.05	1.04	1.09	1.05
Methionine	0.30	0.32	0.32	0.34	0.31	0.31	0.31	0.32	0.44	0.42	0.44	0.47
Cysteine	0.28	0.27	0.26	0.23	0.29	0.27	0.26	0.25	0.29	0.26	0.25	0.23
Threonine	0.65	0.65	0.62	0.60	0.62	0.60	0.58	0.58	0.76	0.73	0.73	0.73
Tryptophan	0.16	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.20	0.19	0.19	0.18
Arginine	0.83	0.73	0.67	0.51	0.77	0.67	0.60	0.57	0.97	0.87	0.79	0.69
Isoleucine	0.58	0.52	0.50	0.47	0.53	0.46	0.45	0.45	0.64	0.61	0.61	0.60
Leucine	1.51	1.45	1.40	1.21	1.49	1.37	1.29	1.22	1.44	1.32	1.25	1.13
Valine	0.71	0.66	0.62	0.59	0.69	0.61	0.57	0.56	0.75	0.71	0.72	0.70
Histidine	0.41	0.38	0.36	0.30	0.40	0.36	0.34	0.32	0.43	0.39	0.36	0.33
Phenylalanine	0.74	0.68	0.64	0.52	0.71	0.63	0.57	0.54	0.79	0.71	0.65	0.57
Glycine	0.63	0.57	0.54	0.44	0.60	0.54	0.50	0.48	0.66	0.59	0.55	0.49
Serine	0.73	0.66	0.63	0.52	0.70	0.63	0.57	0.54	0.78	0.70	0.65	0.57
Alanine	0.94	0.90	0.88	0.78	0.94	0.88	0.83	0.80	0.87	0.80	0.76	0.70
Aspartamine	1.23	1.08	0.99	0.73	1.14	0.96	0.84	0.78	1.50	1.33	1.20	1.03
Glutamine	2.62	2.41	2.29	1.87	2.51	2.22	2.04	1.91	2.81	2.50	2.35	2.08

¹Ctrl = finisher-I, -II, and -III diets formulated with crystalline AA to meet standard ileal digestible (SID) ideal AA requirements for Thr, Met, and Trp; ILE = finisher-I, -II, and -III diets formulated to meet minimum SID Ile requirements without supplemental crystalline Ile, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Met, and Trp; VAL = finisher-I, -II, and -III diets formulated to meet minimum SID Val requirements without supplemental crystalline Val, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Trp, Met, and Ile; NoSBM = finisher-I and -II diets formulated without soybean meal (SBM) but finisher-III diet was formulated with 10.5% SBM and all diets were formulated with crystalline AA to meet SID ideal AA requirements for Lys, Thr, Trp, Met, Ile, and Val.

²10 mg/kg (0.05%, as-fed basis) ractopamine hydrochloride (Paylean; Elanco Animal Health, Greenfield, IN) was included in all diets.

Then, center-cut loins were processed into 1) a 2.5-cm-thick chop for visual and instrumental color, firmness, and marbling data collection; 2) two 3.8-cm-thick chops used for drip loss determination; 3) a 2.5-cm-thick chop for IMF content analysis; and 4) two 2.5-cm-thick chops that were vacuum packaged and immediately frozen for WBSF determinations at a later date.

Pork Quality Data Collection. After exposure to air for 45 min at 2°C, 2 trained, experienced university personnel visually evaluated each SM steak and LM chop for color based on the U.S. (1 = pale, pinkish gray to 6 = dark, purplish red; NPPC, 1999) and Japanese color standards for pork (Nakai et al., 1975) as well as firmness (1 = very soft/very watery to 5 = very firm/dry; NPPC, 1991) and marbling (1 = 1% intramuscular fat to 10 = 10% intramuscular fat; NPPC, 1999). Then, instrumental color (L*, a*, and b*) values were determined from 3 readings on each LM chop and each SM steak with a Hunter MiniScan XE (Hunter Associates Laboratory, Inc., Reston, VA) using illuminant A and a 25-mm viewing diameter. The spectrophotometer was calibrated against standard black and white tiles (Hunter Associates Laboratory, Inc.) before data collection.

Drip loss was determined according to the suspension method of Honikel et al. (1986), with modifica-

tions described by Apple et al. (2000). Briefly, 3.0-cm-diameter cores were manually removed from the center of each 3.8-cm-thick LM chop/SM steak, weighed, and suspended on barbless fishhooks mounted to the lid of a 46- by 66- by 38-cm plastic container. After 48 h of storage at 4°C, each core was removed from its hook, blotted dry on paper towels, and reweighed. The weight loss was divided by the original core weight to calculated drip loss percentage.

Duplicate 5-g samples of the LM were removed from the center of each chop, weighed, placed in 30-mL beakers, and reweighed before being dried for 72 h in a Labconco freeze dryer (Labconco Corp., Kansas City, MO) according to the procedure outlined by Apple et al. (2001). Then, dried LM samples were packaged and submitted to the Poultry Science Department's Analytical Laboratory (University of Arkansas Division of Agriculture, Fayetteville, AR) for quantification of IMF content according to AOAC (2005) method 920.39c.

Warner-Bratzler Shear Force Determination. Semimembranosus steaks and LM chops were thawed for 16 h at 2°C, removed from packaging, deboned (LM chops), trimmed free of any visible external fat, weighed, and cooked to an internal endpoint temperature of 71°C on electric, counter-top griddles (model

07047; National Presto Industries, Inc., Eau Claire, WI). Steaks and chops were turned every 3 min until reaching the endpoint temperature, and internal temperature was monitored with a hand-held, FoodCheck digital thermometer (Comark Instruments, Inc., Beaverton, OR). Immediately after cooking, SM steaks and LM chops were blotted dry on paper towels and reweighed, and the difference between the raw and cooked weights was used to calculate cooking loss percentages. Then, steaks and chops were allowed to cool approximately 2 h to room temperature (21°C) before six 1.3-cm-diameter cores were mechanically removed parallel to the muscle fiber orientation. Each core was subsequently sheared once through the center with a WBSF device attached to an Instron Universal Testing Machine (model 4466; Instron Corp., Canton, MA), equipped with a 55-kg tension/compression load cell and performed at a crosshead speed of 250 mm/min. The average of 6 cores/LM chop or SM steak was averaged for statistical purposes.

Statistical Analyses

Performance, carcass and ham composition, and fresh pork quality data were analyzed as a randomized complete block design, with blocks based on initial BW and pen as the experimental unit. The ANOVA was generated with the mixed models procedure of SAS (SAS Inst., Inc., Cary, NC), with the dietary CP level as the lone fixed effect included in the model. Least squares means were computed, and because of the unequal distribution among the dietary CP treatments, PROC IML of SAS was used to generate the appropriate coefficients for linear, quadratic, and cubic polynomial contrasts.

RESULTS AND DISCUSSION

Growth Performance

Even though ADFI was not ($P \geq 0.61$) affected by reducing dietary CP, both ADG and G:F decreased (linear, $P = 0.05$) as CP was reduced in the finisher-I diets (Table 3). Reducing CP in the finisher-II diets resulted in decreased ADFI (linear, $P = 0.01$) and G:F (quadratic, $P = 0.03$), but ADG was similar ($P \geq 0.17$) across the dietary CP levels. Additionally, ADFI decreased (linear, $P = 0.03$), whereas ADG tended to decrease (linear, $P = 0.07$), with decreasing dietary CP during the finisher-III feeding phase, and G:F responded cubically ($P < 0.01$) with decreasing dietary CP, with pigs fed the ILE diets having greater G:F than those fed either the Ctrl or the VAL diet. Across the entire finishing period, both ADG and ADFI decreased (linear, $P = 0.01$) with decreasing dietary CP; however, overall G:F was similar ($P \geq 0.23$) among the dietary CP treatments.

When growing–finishing pigs were fed reduced-CP diets, without correcting AA deficiencies with synthetic AA, ADG and G:F routinely decrease (Cromwell et al., 1993; Castell et al., 1994; Chen et al., 1995) and ADFI typically increases (Chen et al., 1999; Cline et al., 2016). Yet when reduced-CP diets were formulated with synthetic AA to increase levels of Lys, Met, Thr, and Trp similar to control diets or to meet ideal AA composition, pig performance was either similar to pigs fed the control diets (Kerr et al., 1995; Knowles et al., 1998; Gallo et al., 2014) or improved over that of pigs fed the reduced-CP diets that were not formulated with crystalline AA (Kerr and Easter, 1995; Bunger et al., 2015; van der Meer et al., 2016). Others have reported, however, that ADG (Lee et al., 2001; Gómez et al., 2002; Ball et al., 2013), ADFI (Le Bellego et al., 2002; Figueroa et al., 2012), and G:F (Kerr et al., 2003; Hinson et al., 2009; Figueroa et al., 2012) were decreased in pigs consuming reduced-CP diets, regardless if swine diets were formulated with crystalline AA to meet nutrient requirements.

Dietary inclusion of RAC routinely increases ADG and G:F and decreases ADFI of finishing pigs (Apple et al., 2007), especially when dietary Lys is increased between 0.9 and 1.0% (Webster et al., 2002; Schinckel et al., 2003) or the Lys:ME ratio is increased to between 2.7 to 3.0 g/Mcal (Apple et al., 2004). It was theorized that performance, particularly ADG and G:F, would be decreased by the inclusion of RAC as dietary CP was reduced in the finisher-III diets; however, because all finisher-III diets were formulated with 0.95% SID Lys and a Lys:ME ratio of 2.79 g/Mcal, ADG was only marginally reduced (linear, $P = 0.07$) with decreasing dietary CP, with the greatest reduction in pigs fed the NoSBM diet. Even though analyzed Lys, Met, Cys, Thr, Trp, Ile, and Val concentrations were similar among finisher-III diets, actual concentrations of other AA varied considerably among the reduced-CP diets; therefore, the addition of crystalline Leu and/or His to meet SID levels for these AA may remedy the observed depression in RAC-fed pig performance with decreasing dietary CP.

Carcass and Ham Composition

Both slaughter weight ($P = 0.02$) and HCW ($P = 0.03$) decreased linearly in response to reduced dietary CP levels, but carcass yield was similar ($P \geq 0.70$) among the dietary treatments (Table 4). Smith et al. (1999) reported that pigs fed finishing diets formulated with 14.4% CP were heavier at slaughter than pigs fed an AA-supplemented diet formulated to 10.9% CP, but the majority of research has failed to note a change in slaughter weights by feeding reduced-CP diets (Castell et al., 1994; Suárez-Belloch et al., 2016) or AA-supplemented, reduced-CP diets (Canh et al., 1998;

Table 3. Effect of reducing dietary CP and replacement with crystalline AA during the finisher phases on live growth performance

Item	Dietary CP, ^{1,2} %				SEM	<i>P</i> -value ³		
	Ctrl	ILE	VAL	NoSBM				
	Finisher-I							
	16.04	14.76	14.26	12.65				
	Finisher-II							
	14.55	13.48	12.78	12.38				
Finisher-III								
	16.23	15.27	14.28	13.32		Lin	Quad	Cubic
Pens	9	9	9	9				
Initial BW, kg	61.4	61.6	62.2	61.4	1.93	0.75	0.34	0.43
Finisher-I (62 to 84 kg)								
ADG, kg	1.10	1.08	1.08	1.04	0.020	0.05	0.69	0.44
ADFI, kg	2.95	2.98	2.94	2.94	0.047	0.68	0.75	0.61
G:F	0.37	0.36	0.37	0.35	0.006	0.05	0.78	0.12
BW, kg	84.6	84.2	84.9	83.2	1.95	0.27	0.37	0.27
Finisher-II (84 to 100 kg)								
ADG, kg	1.15	1.07	1.07	1.09	0.041	0.29	0.17	0.67
ADFI, kg	3.39	3.37	3.38	3.20	0.053	0.01	0.10	0.33
G:F	0.34	0.32	0.32	0.34	0.011	0.99	0.03	0.73
BW, kg	100.7	99.2	100.1	98.5	1.79	0.10	0.96	0.12
Finisher-III (100 to 132 kg)								
ADG, kg	1.17	1.19	1.15	1.11	0.037	0.07	0.37	0.67
ADFI, kg	3.42	3.30	3.37	3.16	0.078	0.03	0.46	0.13
G:F	0.34	0.36	0.34	0.35	0.007	0.95	0.69	<0.01
BW, kg	133.5	132.4	132.3	129.5	1.43	0.01	0.39	0.40
Overall (62 to 132 kg)								
ADG, kg	1.15	1.13	1.11	1.08	0.019	0.01	0.84	0.90
ADFI, kg	3.26	3.22	3.23	3.10	0.039	0.01	0.25	0.30
G:F	0.35	0.35	0.34	0.35	0.005	0.38	0.41	0.23

¹Ctrl = finisher-I, -II, and -III diets formulated with crystalline AA to meet standard ileal digestible (SID) ideal AA requirements for Thr, Met, and Trp; ILE = finisher-I, -II, and -III diets formulated to meet minimum SID Ile requirements without supplemental crystalline Ile, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Met, and Trp; VAL = finisher-I, -II, and -III diets formulated to meet minimum SID Val requirements without supplemental crystalline Val, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Trp, Met, and Ile; NoSBM = finisher-I and -II diets formulated without soybean meal (SBM) but finisher-III diet was formulated with 10.5% SBM and all diets were formulated with crystalline AA to meet SID ideal AA requirements for Lys, Thr, Trp, Met, Ile, and Val.

²10 mg/kg ractopamine hydrochloride (Elanco Animal Health, Greenfield, IN) was included in all finisher-III diets, and dietary Lys was increased to achieve a SID Lys content of 0.954%.

³Probability values for the linear (Lin), quadratic (Quad), and cubic response to reductions in dietary CP level.

Carpenter et al., 2004; Ball et al., 2013). In agreement with the current results, Valaja et al. (1993) and Van Lunen and Cole (1996) observed linear reductions in HCW with decreasing CP in AA-fortified diets, but others have reported that HCW was not affected by reducing CP from as high as 25.0% to as low as 11.9% in diets formulated without crystalline AA (Castell et al., 1994; Chen et al., 1999; Suárez-Belloch et al., 2016). In addition, Ball et al. (2013) reported that carcass yield linearly decreased as CP was reduced from 18.8 to 13.5% in AA-supplemented diets, whereas Van Lunen and Cole (1996) observed a linear increase in carcass yield as CP was reduced from 26.2 to 11.5% in AA-supplemented diets, yet carcass yield was similar among dietary CP levels in swine diets formulated with (Barea et al., 2006; Hinson et al., 2009; Madeira et al., 2013a) or without crystalline

AA (Chen et al., 1999; Tous et al., 2014; Suárez-Belloch et al., 2016). The discrepancies among experiments are likely a response to vast differences in pig genotypes, ending live weights, and carcass leanness.

Both Fat-O-Meat^{er}-measured 10th-rib fat and LM depths, along with calculated fat-free lean yield, were not ($P \geq 0.13$) affected by any dietary CP treatment (Table 4). It is generally accepted that 10th-rib fat depth increases as CP is decreased in swine diets (Chen et al., 1995, 1999; Carpenter et al., 2004; Suárez-Belloch et al., 2016), especially when the reduction in dietary CP is 3 percentage units or more (Kerr et al., 1995; Smith et al., 1999; Jha et al., 2013). In addition, reducing dietary CP has been repeatedly shown to reduce LM area (Cromwell et al., 1993; Chen et al., 1995, 1999; Goerl et al., 1995), especially between diets differing in CP

Table 4. Effect of reducing dietary CP and replacement with crystalline AA during the finisher phases on pork carcass composition

Item	Dietary CP, ^{1,2} %				SEM	<i>P</i> -value ³		
	Ctrl	ILE	VAL	NoSBM				
	Finisher-I							
	16.04	14.76	14.26	12.65				
	Finisher-II							
	14.55	13.48	12.78	12.38				
	Finisher-III							
	16.23	15.27	14.28	13.32		Lin	Quad	Cubic
Pens	9	9	9	9				
Slaughter wt, kg	127.3	126.8	126.2	124.0	1.73	0.02	0.38	0.69
HCW, kg	99.0	98.5	97.8	96.6	1.22	0.03	0.62	0.89
Carcass yield, ⁴ %	77.8	77.8	77.7	78.0	0.44	0.83	0.70	0.76
Fat depth, mm	18.4	18.8	19.5	18.4	0.55	0.80	0.13	0.31
LM depth, mm	58.1	59.7	59.1	58.5	0.74	0.86	0.14	0.56
Lean yield, %	52.4	52.6	52.3	52.6	0.24	0.89	0.91	0.30

¹Ctrl = finisher-I, -II, and -III diets formulated with crystalline AA to meet standard ileal digestible (SID) ideal AA requirements for Thr, Met, and Trp; ILE = finisher-I, -II, and -III diets formulated to meet minimum SID Ile requirements without supplemental crystalline Ile, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Met, and Trp; VAL = finisher-I, -II, and -III diets formulated to meet minimum SID Val requirements without supplemental crystalline Val, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Trp, Met, and Ile; NoSBM = finisher-I and -II diets formulated without soybean meal (SBM) but finisher-III diet was formulated with 10.5% SBM and all diets were formulated with crystalline AA to meet SID ideal AA requirements for Lys, Thr, Trp, Met, Ile, and Val.

²10 mg/kg ractopamine hydrochloride (Elanco Animal Health, Greenfield, IN) was included in all finisher-III diets, and dietary Lys was increased to achieve a SID Lys content of 0.954%.

³Probably values for the linear (Lin), quadratic (Quad), and cubic response to reductions in dietary CP level.

⁴(HCW/BW recorded immediately prior to transportation) × 100.

levels by 3 or more percentage units (Kerr et al., 1995, 2003; Cisneros et al., 1996), but LM depth does not appear to be affected by differing dietary CP levels (Canh et al., 1998; Prandini et al., 2013; Tous et al., 2014). The result of increasing carcass fatness with either a reduction in LM area or no change in LM depth results in reductions in estimated carcass lean yields (Cromwell et al., 1993; Hansen and Lewis, 1993; Carpenter et al., 2004). The lack of an effect of reducing CP in swine finishing diets in the present study may be that SID requirements for the first 6 limiting AA were met with crystalline AA, and even though CP varied by 3.39 percentage units in finisher-I diets, CP varied only 2.17 and 2.91 percentage units in finisher-II and -III diets, respectively. Furthermore, the inclusion of RAC in the finisher-III diets routinely reduces 10th-rib fat depth and increases LM depth (Apple et al., 2007); therefore, it is possible that the beneficial effects of feeding RAC on fat and LM depths, as well as the resultant carcass cutability, may be more responsive to the AA composition of the diet rather than actual dietary CP level.

Fresh ham weights were similar ($P \geq 0.10$) among dietary CP treatments, even though the weights of the flat (linear, $P = 0.01$), pillow (linear, $P = 0.06$), and all bone (quadratic, $P = 0.06$) decreased with decreasing dietary CP (Table 5). However, when expressed as a percentage of the fresh ham weight, the proportions of total lean and bone did not ($P \geq 0.15$) differ among

dietary CP treatments, even though the proportion of total fat tended to increase (linear, $P = 0.09$) as the CP level was reduced in swine finishing diets.

Neither fresh ham weight (Castell et al., 1994; Fabian et al., 2002; Schiavon et al., 2015) nor ham yield as a percentage of the HCW (Prandini et al., 2013; Gallo et al., 2015; Suárez-Belloch et al., 2016) has been shown to be altered by dietary CP levels. Knowles et al. (1998) reported that ham lean and fat weights and yields did not differ between pigs fed 15.5% CP and pigs fed 11.7% CP, and Kerr et al. (2003) reported that the weights of ham lean and fat were similar between carcasses from pigs fed high-CP diets (15.5 to 15.8% and 13.4 to 13.7% in the early- and late-finisher diets, respectively) and those fed low-CP diets (12.6 to 13.0% and 10.7 to 11.1% in the early- and late-finisher diets, respectively). Conversely, both Valaja et al. (1993) and Barea et al. (2006) reported that the percentage of dissected ham lean decreased linearly with decreasing CP, whereas Barea et al. (2006) noted a linear increase in the proportion of dissected ham fat as CP was reduced in AA-supplemented swine diets.

Fresh Pork Quality Characteristics

Longissimus Muscle Quality. Ultimate (48-h) LM pH values, drip loss percentages, and firmness scores were not affected ($P \geq 0.33$) by dietary CP level

Table 5. Effect of reducing dietary CP and replacement with crystalline AA during the finisher phases on fresh ham composition

Item	Dietary CP, ^{1,2} %				SEM	<i>P</i> -value ³		
	Ctrl	ILE	VAL	NoSBM				
	Finisher-I							
	16.04	14.76	14.26	12.65				
	Finisher-II							
	14.55	13.48	12.78	12.38				
	Finisher-III							
	16.23	15.27	14.28	13.32		Lin	Quad	Cubic
Pens ⁴	9	9	9	9				
Fresh ham wt, kg	11.8	11.7	11.7	11.4	0.17	0.10	0.43	0.80
Muscle wt, ⁵ kg								
Pillow	1.89	1.90	1.82	1.81	0.043	0.06	0.82	0.41
Flat	2.19	2.16	2.08	2.06	0.042	0.01	0.93	0.64
ST	0.63	0.63	0.62	0.60	0.024	0.32	0.67	0.97
QF	1.38	1.36	1.34	1.31	0.034	0.09	0.96	0.98
Lean trim	2.23	2.22	2.22	2.19	0.063	0.61	0.88	0.79
Fat wt, kg	2.17	2.17	2.33	2.21	0.067	0.33	0.33	0.11
Bone wt, kg	1.21	1.26	1.23	1.19	0.032	0.39	0.06	0.54
Yield, ⁶ %								
Total lean	70.81	70.39	69.32	70.04	0.582	0.15	0.27	0.30
Total fat	18.52	18.55	19.94	19.34	0.605	0.09	0.53	0.15
Total bone	10.30	10.76	10.59	10.45	0.263	0.77	0.19	0.50

¹Ctrl = finisher-I, -II, and -III diets formulated with crystalline AA to meet standard ileal digestible (SID) ideal AA requirements for Thr, Met, and Trp; ILE = finisher-I, -II, and -III diets formulated to meet minimum SID Ile requirements without supplemental crystalline Ile, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Met, and Trp; VAL = finisher-I, -II, and -III diets formulated to meet minimum SID Val requirements without supplemental crystalline Val, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Trp, Met, and Ile; NoSBM = finisher-I and -II diets formulated without soybean meal (SBM) but finisher-III diet was formulated with 10.5% SBM and all diets were formulated with crystalline AA to meet SID ideal AA requirements for Lys, Thr, Trp, Met, Ile, and Val.

²10 mg/kg ractopamine hydrochloride (Elanco Animal Health, Greenfield, IN) was included in all finisher-III diets, and dietary Lys was increased to achieve a SID Lys content of 0.954%.

³Probability values for the linear (Lin), quadratic (Quad), and cubic response to reductions in dietary CP level.

⁴Subsampling of 2 randomly selected hams from each pen.

⁵Pillow = semimembranosus and adductor muscles; Flat = biceps femoris; ST = semitendinosus; QF = quadriceps complex.

⁶Percentage of the fresh, whole ham weight.

(Table 6). There is little evidence to suggest that reducing CP in swine finishing diets alters LM pH (Alonso et al., 2010; Cho et al., 2012; Madeira et al., 2014a), and even though Tous et al. (2014) reported greater drip loss percentages from the LM of pigs fed 13.0 rather than 10.6% CP, neither water-holding capacity measures (Goerl et al., 1995; Alonso et al., 2010; Ma et al., 2015) nor firmness scores (Castell et al., 1994; Fabian et al., 2002; Hinson et al., 2009) of the LM appear to be affected by dietary CP level.

Japanese color scores tended to increase (quadratic, $P = 0.06$) with decreasing dietary CP, but U.S. color scores, as well as instrumental color values, were similar ($P \geq 0.13$) among dietary CP treatments (Table 6). Castell et al. (1994) reported that LM color scores actually decreased linearly as dietary CP was reduced from 17.6 to 11.9% in swine diets, but others have failed to note an effect of feeding reduced-CP diets on LM color scores (Fabian et al., 2002; Yang et al., 2008; Hinson et

al., 2009). Goerl et al. (1995) reported linear increases in the redness (a^*) and yellowness (b^*) values of LM chops as CP was reduced from 25 to 10%; otherwise, feeding finishing pigs reduced-CP diets has no appreciable effects on instrumental color of the LM (Yang et al., 2008; Madeira et al., 2014a; Suárez-Belloch et al., 2016), which is in agreement with the current results.

In a recent meta-analysis, Bohrer and Boler (2017) reported that National Pork Producers Council (1999) marbling scores were positively correlated with IMF content but accounted for less than 25% of the variation in actual IMF content. Similarly, in the present experiment, marbling scores did not correspond well with ether-extracted IMF, yet both LM marbling scores (linear, $P = 0.02$) and IMF content (linear, $P = 0.03$) increased as CP was reduced in the finisher diets (Table 6). Although IMF values were at the upper range of IMF content reported by Bohrer and Boler (2017) from 101 peer-reviewed journal articles, results of the current

Table 6. Effect of reducing dietary CP and replacement with crystalline AA during the finisher phases on quality characteristics of the LM

Item	Dietary CP, ^{1,2} %				SEM	<i>P</i> -value ³		
	Ctrl	ILE	VAL	NoSBM				
	Finisher-I							
	16.04	14.76	14.26	12.65				
	Finisher-II							
	14.55	13.48	12.78	12.38				
	Finisher-III							
16.23	15.27	14.28	13.32	Lin	Quad	Cubic		
Pens ⁴	9	9	9	9				
48-h pH	5.71	5.77	5.73	5.78	0.042	0.33	0.92	0.35
Drip loss, %	1.65	1.81	1.64	1.60	0.185	0.70	0.61	0.59
Japanese color ⁵	2.7	3.0	2.8	2.7	0.11	0.99	0.06	0.23
U.S. color ⁶	3.0	3.4	3.2	3.1	0.14	0.81	0.13	0.28
Lightness (L*) ⁷	45.24	44.23	45.38	45.90	0.665	0.27	0.23	0.33
Redness (a*) ⁷	7.36	7.73	7.78	7.79	0.240	0.16	0.40	0.76
Yellowness (b*) ⁷	6.49	6.40	7.09	6.75	0.338	0.27	0.67	0.19
Firmness ⁸	2.8	2.7	2.6	2.7	0.09	0.55	0.41	0.96
Marbling ⁹	1.7	2.0	2.2	2.3	0.17	0.02	0.47	0.74
IMF ¹⁰ content, %	5.56	5.93	6.71	6.88	0.552	0.03	0.83	0.64
Cooking loss, %	22.05	20.38	20.89	21.56	0.533	0.69	0.04	0.40
Shear force, kg	5.66	5.15	5.16	5.75	0.327	0.86	0.10	0.97

¹Ctrl = finisher-I, -II, and -III diets formulated with crystalline AA to meet standard ileal digestible (SID) ideal AA requirements for Thr, Met, and Trp; ILE = finisher-I, -II, and -III diets formulated to meet minimum SID Ile requirements without supplemental crystalline Ile, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Met, and Trp; VAL = finisher-I, -II, and -III diets formulated to meet minimum SID Val requirements without supplemental crystalline Val, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Trp, Met, and Ile; NoSBM = finisher-I and -II diets formulated without soybean meal (SBM) but finisher-III diet was formulated with 10.5% SBM and all diets were formulated with crystalline AA to meet SID ideal AA requirements for Lys, Thr, Trp, Met, Ile, and Val.

²10 mg/kg ractopamine hydrochloride (Elanco Animal Health, Greenfield, IN) was included in all finisher-III diets, and dietary Lys was increased to achieve a SID Lys content of 0.954%.

³Probability values for the linear (Lin), quadratic (Quad), and cubic response to reductions in dietary CP level.

⁴Subsampling of 2 randomly selected loins/pen.

⁵1 = pale gray to 6 = dark purple (Nakai et al., 1975).

⁶1 = pale, pinkish gray to 6 = dark, purplish red (NPPC, 1999).

⁷L* = measure of darkness to lightness (greater L* value indicates a lighter color); a* = measure of redness (greater a* value indicates a redder color); b* = measure of yellowness (greater b* value indicates a more yellow color).

⁸1 = very soft/very watery to 5 = very firm/dry (NPPC, 1991).

⁹1 = 1% intramuscular fat to 10 = 10% intramuscular fat (NPPC, 1999).

¹⁰IMF = intramuscular fat.

trial concur with a number of studies reporting linear increases in LM IMF content with decreasing dietary CP (Castell et al., 1994; Goerl et al., 1995; Suárez-Belloch et al., 2016). Visually appraised marbling scores are not always affected by feeding pigs reduced-CP diets (Fabian et al., 2002; Hinson et al., 2009); however, research indicates that LM IMF content was increased by 34 and 105% with reductions in dietary CP levels of 2 (Cisneros et al., 1996; Teye et al., 2006; Alonso et al., 2010), 3 (Kerr et al., 1995; Madeira et al., 2014a,b), 4 (da Costa et al., 2004; Madeira et al., 2013a; Wood et al., 2013), and 5 percentage units (Karlsson et al., 1993; Essén-Gustavsson et al., 1994; Cameron et al., 1999).

Semimembranosus Quality. Although 48-h pH was similar ($P \geq 0.68$) among dietary CP levels, drip loss percentages in the SM were reduced (quadratic, $P =$

0.04) with decreasing dietary CP (Table 7). Otherwise, reducing CP in swine finishing diets had no effect on subjective color scores ($P \geq 0.20$), instrumental color values ($P \geq 0.17$), firmness scores ($P \geq 0.12$), or marbling scores ($P \geq 0.32$). With the exception of Prandini et al. (2013), who observed that reducing dietary CP of finishing pigs by more than 3 percentage units reduced L* values and increased a* values of the SM, the available research indicates that dietary protein has no effect on the ultimate pH (Ruusunen et al., 2007; Tous et al., 2014; Schiavon et al., 2015), instrumental and visual color values (Ruusunen et al., 2007; Schiavon et al., 2015), or water-holding capacity of pork SM (Ruusunen et al., 2007). In contrast to the results of the present study, Schiavon et al. (2015) reported that SM marbling scores were increased by reducing dietary CP

Table 7. Effect of reducing dietary CP and replacement with crystalline AA during the finisher phases on quality characteristics of the semimembranosus

Item	Dietary CP, ^{1,2} %				SEM	<i>P</i> -value ³		
	Ctrl	ILE	VAL	NoSBM				
	Finisher-I							
	16.04	14.76	14.26	12.65				
	Finisher-II							
	14.55	13.48	12.78	12.38				
Finisher-III								
	16.23	15.27	14.28	13.32		Lin	Quad	Cubic
Pens ⁴	9	9	9	9				
48-h pH	5.88	5.88	5.85	5.87	0.050	0.72	0.86	0.68
Drip loss, %	1.55	1.36	1.22	1.42	0.103	0.23	0.04	0.49
Japanese color ⁵	3.7	3.9	3.9	3.8	0.14	0.99	0.20	0.76
U.S. color ⁶	4.1	4.3	4.3	4.2	0.12	0.58	0.20	0.85
Lightness (L*) ⁷	40.73	40.51	40.58	41.54	0.770	0.48	0.45	0.86
Redness (a*) ⁷	10.58	10.60	11.01	10.52	0.345	0.89	0.46	0.41
Yellowness (b*) ⁷	8.23	8.11	8.80	8.40	0.303	0.38	0.64	0.17
Firmness ⁸	2.6	2.7	2.8	2.7	0.08	0.12	0.20	0.67
Marbling ⁹	2.2	2.3	2.4	2.5	0.16	0.32	0.93	0.97
Cooking loss, %	19.70	20.38	20.37	21.05	0.710	0.21	0.99	0.66
Shear force, kg	2.67	3.23	3.05	3.37	0.142	<0.01	0.37	0.04

¹Ctrl = finisher-I, -II, and -III diets formulated with crystalline AA to meet standard ileal digestible (SID) ideal AA requirements for Thr, Met, and Trp; ILE = finisher-I, -II, and -III diets formulated to meet minimum SID Ile requirements without supplemental crystalline Ile, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Met, and Trp; VAL = finisher-I, -II, and -III diets formulated to meet minimum SID Val requirements without supplemental crystalline Val, but crystalline AA were added to meet SID ideal AA requirements for Lys, Thr, Trp, Met, and Ile; NoSBM = finisher-I and -II diets formulated without soybean meal (SBM) but finisher-III diet was formulated with 10.5% SBM and all diets were formulated with crystalline AA to meet SID ideal AA requirements for Lys, Thr, Trp, Met, Ile, and Val.

²10 mg/kg ractopamine hydrochloride (Elanco Animal Health, Greenfield, IN) was included in all finisher-III diets, and dietary Lys was increased to achieve a SID Lys content of 0.954%.

³Probability values for the linear (Lin), quadratic (Quad), and cubic response to reductions in dietary CP level.

⁴Subsampling of 2 randomly selected hams/pen.

⁵1 = pale gray to 6 = dark purple (Nakai et al., 1975).

⁶1 = pale, pinkish gray to 6 = dark, purplish red (NPPC, 1999).

⁷L* = measure of darkness to lightness (greater L* value indicates a lighter color); a* = measure of redness (greater a* value indicates a redder color); b* = measure of yellowness (greater b* value indicates a more yellow color).

⁸1 = very soft/very watery to 5 = very firm/dry (NPPC, 1991).

⁹1 = 1% intramuscular fat to 10 = 10% intramuscular fat (NPPC, 1999).

by more than 3 percentage units, whereas Cisneros et al. (1996), Wood et al. (2013), and Tous et al. (2014) reported that reducing CP between 2.4 and 3.9 percentage units increased the IMF content of the SM.

There is compelling evidence that the regulation of fat deposition is depot dependent and regulated by protein inclusion rates. Because IMF is highly metabolic and the last fat depot to develop, it is the most responsive to dietary manipulations (Gondret and Lebret, 2002; Doran et al., 2006). Deposition of fat when intake of protein, energy, or both protein and energy were restricted varied, with the energy restriction alone decreasing fat deposition in subcutaneous fat and IMF depots (Madeira et al., 2013b, 2014b). Interestingly, restricted protein intake (with or without energy restriction) depressed fat deposition in subcutaneous fat but dramatically increased IMF content between 40 and 48%.

Although the underlying mechanism or mechanisms for increased IMF associated with feeding swine reduced-CP diets is not fully understood, the available information would suggest it is a combination of enhanced lipid anabolism and reduced lipid catabolism in combination with an increase in adipogenesis, or hyperplasia. Gondret and Lebret (2002) found that the number of intramuscular clustered adipocytes increased in response to reducing the intake of dietary CP by growing-finishing pigs. At the molecular level, feeding pigs a reduced-CP diet decreased the expression of *transforming growth factor-β* (Hamill et al., 2013), a factor associated with suppression of adipocyte differentiation (Tan et al., 2008), and increased the adipogenic factor *peroxisome proliferator-activated receptor-γ* (PPAR γ ; Katsumata et al., 2005, 2008; Wang et al., 2012) and the lipogenic factor *sterol regulatory element binding protein-1* (SREBP1; Chen et al., 2008;

Wang et al., 2012; Dannenberger et al., 2014) in the LM. Furthermore, a number of studies have demonstrated that reducing dietary CP fed pigs increased the expression of key enzymes involved in de novo fatty acid synthesis, specifically acetyl-CoA carboxylase (Doran et al., 2006; Cánovas et al., 2009; Wang et al., 2012), fatty acid synthase (Wang et al., 2012; Madeira et al., 2013b), and stearoyl-CoA desaturase (da Costa et al., 2004; Doran et al., 2006; Cánovas et al., 2009). Finally, restricting CP intake has also been shown to decrease muscle respiration rate (Adeola and Young, 1989), free carnitine content (Katsumata et al., 2005), and both mRNA and protein expression levels of the lipolytic enzymes hormone-sensitive lipase and carnitine palmitoyltransferase-1 (Wang et al., 2012) in porcine IMF.

Cooked Pork Quality Characteristics

Cooking loss percentages decreased (quadratic, $P = 0.04$) in LM chops (Table 6), but not among SM steaks ($P \geq 0.21$), as CP was reduced in the finishing diets (Table 7). In contrast, Suárez-Belloch et al. (2016) reported that cooking losses increased linearly as dietary CP was reduced from 21.6 to 13.5%, whereas Nissen and Oksbjerg (2011) and Needham and Hoffman (2015) observed that feeding reduced-CP diets increased LM cooking losses compared with feeding elevated or controlled CP diets, yet others have failed to demonstrate an effect of reducing dietary CP from as high as 25.0% to as low as 10.0% on cooking loss percentages (Castell et al., 1994; Goerl et al., 1995; Teye et al., 2006).

On the other hand, WBSF values for LM chops were not affected ($P \geq 0.10$) by reductions in dietary CP (Table 6); however, WBSF values of SM steaks increased (linear, $P < 0.01$) as CP was reduced in swine finishing diets (Table 7). Neither WBSF values nor sensory panel tenderness scores of pork LM chops were affected by the dietary CP levels fed finishing pigs (Teye et al., 2006; Madeira et al., 2013a, 2014a); however, both Goerl et al. (1995) and Suárez-Belloch et al. (2016) observed that WBSF values decreased quadratically as dietary CP was reduced from 25 to 10% in swine diets. Additionally, reducing CP in finishing diets by more than 3 percentage units has been shown to reduce WBSF values of LM chops (Karlsson et al., 1993; Essén-Gustavsson et al., 1994; Nissen and Oksbjerg, 2011) and increase sensory panelists' ratings of tenderness (Castell et al., 1994; Cameron et al., 1999; Alonso et al., 2010). Interestingly, Nissen and Oksbjerg (2011) reported that reducing dietary CP by 5 to 8 percentage units reduced calpastatin activity in pork LM, whereas reductions in CP levels fed to pigs in the present experiment were not as severe. On the other hand, in a meta-analysis of the available

research, Apple et al. (2007) observed that the increases in WBSF values of pork from pigs fed RAC were more closely related to the elevated dietary Lys levels typically required to optimize the effects of RAC on performance and carcass cutability than dietary inclusion of RAC. Moreover, Xiong et al. (2006) found that feeding pigs 20 mg/kg RAC for 28 d before slaughter promoted calpastatin activity and reduced the rate of calpain-dependent proteolysis, thereby delaying the postmortem aging process by approximately 4 d compared with the LM from pigs fed diets devoid of RAC. Therefore, the additional Lys included in the finisher-III diets (and not the absolute CP level per se), coupled with the short, 2-d postmortem aging period, may explain the observed increases in WBSF of SM steaks with decreasing dietary CP in the present experiment.

Conclusions

Even though reducing dietary CP, while meeting the SID requirements for Lys, Thr, Trp, Met, Ile, and Val with crystalline AA, decreased finishing pig performance, it should be noted that the observed 6.1 and 4.9% decreases in overall ADG and ADFI, respectively, were observed only in pigs consuming diets with the greatest reduction in CP (NoSBM). Furthermore, formulating swine diets with crystalline AA to reduce dietary CP has been repeatedly shown to reduce nitrogen excretion from growing–finishing pigs (Canh et al., 1998; Zervas and Zijlstra, 2002; Atakora et al., 2011) and ammonia emissions from swine slurry (Canh et al., 1998; Portejoie et al., 2004; Le et al., 2009) or exhausted air (Hayes et al., 2004; Panetta et al., 2006) between 30 and 50%. Using the equation of Canh et al. (1998), calculated ammonia emissions were reduced by between 14.0 to 41.5% by the reductions in dietary CP used in the current study. More importantly, LM IMF content increased linearly as dietary CP was reduced in the finisher diets, whereas feeding finishing pigs reduced-CP, AA-supplemented diets had no deleterious effects on pork carcass composition, fresh pork color, or water-holding capacity of both the LM and SM. Therefore, the modest reductions in dietary CP and inclusion of the crystalline AA to meet minimum SID requirements for the first 6 rate-limiting AA may be an effective nutritional strategy to reduce nitrogen excretion with minimal to no effects on pig performance and pork carcass characteristics.

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