Modeling the effects of standardized ileal digestible valine to lysine ratio on growth performance of nursery pigs[1,2]

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ABSTRACT: Two experiments evaluated the effects of increasing Lys and Val on growth performance of nursery pigs. In Exp. 1,300 nursery pigs (PIC 327 × 1,050, initially 6.7 ± 1.4 kg BW) were randomly allotted to 1 of 6 diets containing 1.10, 1.20, 1.30, 1.40, 1.50, or 1.60% standardized ileal digestible (SID) Lys, with 10 pens per dietary treatment and 5 pigs per pen. Linear and nonlinear mixed models were fitted to estimate dose responses. From d 0 to 14, and for the overall 28 d period, ADG and G:F increased (linear, $P < 0.001$) as SID Lys increased, with no evidence of differences in ADFI. Dose response modeling indicated the SID Lys requirement for ADG and G:F was at 1.45% using a broken line linear (BLL) and greater than 1.60% using a quadratic polynomial (QP) model. In Exp. 2, 280 nursery pigs (PIC 327 × 1,050, initially 6.5 ± 1.3 kg BW) were allotted to 1 of 7 diets containing SID Val:Lys ratios of 50, 57, 63, 68, 73, 78, or 85%. The dietary SID Lys concentration 1.24% SID Lys which was below the estimated requirement from Exp. 1 and ensured the Val:Lys ratio was not underestimated. From d 0 to 14, ADG, ADFI, and G:F increased (quadratic, $P < 0.039$) with increasing SID Val:Lys. For ADG, the best fitting model was a BLL, with a breakpoint estimate of 62.9% SID Val:Lys [52.2, 73.7] ratio while for G:F the best fit model was a quadratic polynomial with a maximum G:F at 71.7% SID Val:Lys (95%CI:[58, > 85]). Average daily feed intake was also modeled with a quadratic polynomial and maximized at 73.7% Val:Lys (95% CI: [61, > 85]). In conclusion, the Val requirement ranged from approximately 63 to 74% of Lys depending on the response criteria modeled.

Key words: amino acids, growth, lysine, nursery, pig, valine

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INTRODUCTION

Amino acid requirement estimates are often expressed on a standardized ileal digestible (SID) basis and in ratios relative to Lys, which is typically the first limiting AA in corn and soybean meal diets for swine. While much is understood about the Lys requirement, it is important that it be determined prior to evaluating another limiting AA. The NRC (2012) estimates the SID Lys requirement for 7- to 11-kg pigs at 1.35%. Wiltafsky et al. (2009), Gaines et al. (2011), and Nemechek et al. (2014) reported that a SID Val:Lys ratio of approximately 65 to 67% was necessary for optimal growth of pigs ranging from 8 to 32 kg of BW. These values are often used as a recommendation for formulating diets under conditions of untested requirements.

When determining an AA requirement, advanced statistical methods may allow researchers to predict biological requirements with enhanced accuracy and precision. For example, Gonçalves et al. (2016a) detailed modeling strategies that account for heterogeneity of residual variance, also known as heteroskedasticity. Heteroskedasticity seems to be a rather common phenomenon in animal agri-

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culture (Cernicchiaro et al., 2013; Gonçalves et al., 2015; Gonçalves et al., 2016a) and is characterized by unequal dispersion of residuals across groups of interest. Heteroskedasticity can be explicitly accommodated using a mixed modeling framework, which then translates into differential inferential precision across groups (Littell et al., 2006). This can be useful in the context of titration studies to characterize dose–response curves (Gonçalves et al., 2016b) and better predict nutrient requirements with enhanced precision.

Therefore, the objectives of these experiments were, first to validate the Lys in our experimental setting; and second, to determine the Val requirement over a dose–response for growth performance of 7- to 11-kg nursery pigs in a marginally Lys deficient scenario using a mixed modeling framework accounting for heteroskedasticity.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment.

General

Similar protocols were used in both experiments. Pigs (PIC 327 × 1,050, Hendersonville, TN) were weaned at approximately 21 d of age, placed in nursery pens according to BW and gender, and fed a common pelleted starter diet for 6 (Exp. 1) or 5 d (Exp. 2). Then, pens of pigs were allotted to dietary treatments, and this was considered d 0 of the study. Each pen (1.52 × 1.52 m, Exp. 1; 1.52 × 1.22 m, Exp. 2) contained a 4-hole dry self-feeder and a nipple-waterer for ad libitum access to feed and water. Both experiments were conducted at the Kansas State University Swine Teaching and Research Center. Pens of pigs and feeders were weighed on d 0, 14, and 28 to calculate ADG, ADFI, and G:F.

Dietary treatments were fed for 14 d followed by a common diet from d 14 to 28. Dietary treatments were corn- and soybean meal-based and contained 10% dried whey, fed in meal form. Crystalline AA replaced corn in diets as treatment levels of AA increased. During the common diet phase, diets were also corn- and soybean meal-based containing no specialty protein sources and formulated to 1.22% SID Lys. In Exp. 1, NRC (2012) ingredient nutrient values and SID AA coefficients were used in diet formulation. In Exp. 1, enzymatically treated soybean meal (HP 300, Hamlet Protein, Findlay, OH) was included at 10% and AA values and SID coefficients provided by the manufacturer were used. For Exp. 2, corn, soybean meal, and dried whey were analyzed for AA content prior to formulation (Table 1). All diets were fed in meal form and prepared at the O.H. Kruse Feed Technology and Innovation Center located in Manhattan, KS. For both experiments, basal diets were manufactured for the extreme dietary treatments, and then blended at the feed mill to create the intermediate levels. Samples of experimental diets were submitted (Ward Laboratories, Kearney, NE) for analysis of DM (method 935.29; AOAC International, 2012), crude fiber [method 978.10; AOAC International, 2012 for preparation and Ankom 2000 (Ankom Technology, Fairport, NY) Fiber Analyzer (Ankom Technology)], ash (method 942.05; AOAC International, 2012), ether extract [method 920.39 a; AOAC International, 2012 for preparation and ANKOM XT20 Fat Analyzer (Ankom Technology, Fairport, NY)], Ca and P [method 968.08 b; AOAC International, 2012 for preparation using ICAP 6500 (ThermoElectron Corp., Waltham, MA)], Additional samples were submitted (Ajinomoto Heartland, Inc., Chicago, IL) for AA analysis (excluding Trp; method 994.12; AOAC International, 2012) and Trp (method 13904:2005; ISO, 2005; Ajinomoto Heartland, Inc., Chicago, IL).

Table 1. Chemical analysis of ingredients for Exp. 2[1,2]

Item, %	Corn	Soybean meal	Dried whey
DM	88.81	89.09	90.04
CP	9.01	47.00	11.84
Total AA			
Lys	0.29	2.88	0.79
Ile	0.31	2.09	0.65
Leu	1.10	3.51	1.07
Met	0.18	0.66	0.16
Thr	0.30	1.80	0.68
Trp	0.07	0.65	0.22
Val	0.40	2.12	0.59
His	0.24	1.17	0.18
Phe	0.43	2.35	0.37
Standardized ileal digestible AA, % (Calculated)			
Lys	0.21	2.56	0.77
Ile	0.25	1.86	0.62
Leu	0.95	3.09	1.05
Met	0.15	0.59	0.16
Thr	0.23	1.53	0.61
Trp	0.06	0.59	0.21
Val	0.32	1.84	0.56
His	0.20	1.05	0.17
Phe	0.36	2.07	0.34

[1]Analyzed for AA content at Ajinomoto Heartland, Inc. (Chicago, IL).

[2]Standardized ileal digestible (SID) concentration calculated using SID coefficients from the NRC (NRC, 2012).

Experiment 1

A total of 300 nursery pigs (initially 6.7 ± 0.06 kg BW) were used to evaluate the effects of increasing SID Lys on growth performance. Dietary treatments were

formulated to contain 1.10, 1.20, 1.30, 1.40, 1.50, and 1.60% SID Lys (Table 2). All other AAs exceeded estimated requirements on a ratio relative to Lys. After 6 d in the nursery, pens were randomly allocated to dietary treatments in a completely randomized design resulting in 10 pens per dietary treatment with 5 pigs per pen.

Experiment 2

A total of 280 nursery pigs (initially 6.5 ± 0.03 kg BW) were used to evaluate the effects of increasing SID Val:Lys ratio on growth performance. Dietary treatments were formulated to contain SID Val at 50, 57, 63, 68, 73, 78, and 85% of Lys (Table 3). Based on the results in Exp.1, dietary treatments were formulated to contain 1.24% SID Lys to ensure pigs were below their requirement. After 5 d in the nursery, pens of pigs were blocked by initial BW and then randomly assigned to dietary treatments in a randomized complete block design, resulting in 8 pens per dietary treatment and 5 pigs per pen.

Statistical Analysis

Statistical analyses were performed separately for each experiment following the approach proposed by Gonçalves et al. (2016a). Briefly, preliminary analyses steps included fitting a base mixed model to response variables, recognizing pen as the experimental unit and their respective designs (i.e., Exp.1: completely randomized design; Exp. 2: a randomized complete block design). For Exp. 1, the linear predictor included a fixed effect of dietary treatment whereas for Exp. 2, it included a fixed effect of dietary treatment and a random effect of BW block. For Exp. 2, initial BW was also used as an explanatory covariate in all base models as it enhanced model fit beyond that of the random effect of block. For ADFI, the random effect of block was removed from the model as its variance component estimate converged to 0. For each response, the base model was also used to explore heterogeneity of residual variances across dietary treatments using Bayesian Information Criteria (BIC) to decide on best fitting approaches to account for heteroscedasticity and thus meet modeling assumptions. For Exp. 1, heterogeneous residual variances were specified for G:F. For Exp. 2, heterogeneous residual variances were specified for ADG and ADFI. For each response, studentized residuals were used to assess model assumptions. Estimated least square means and corresponding SEM were obtained for each dietary treatment. Orthogonal polynomial contrasts of first and second order were built with coefficients modified to accommodate unequal spacing between dietary treatments. Linear and quadratic trends were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P < 0.10$. For Exp. 1, data from 1 pen on the 1.30% SID Lys treatment and 1 pen on 1.40% SID Lys treatment were excluded from analysis after review of daily pig monitoring indicated pigs with poor physical condition that did not appear to be treatment related.

Table 2. Diet composition (as-fed basis), Exp. 1[1]

Item	Formulated SID[2] Lys, %		Common phase
	1.10	1.60	
Ingredient, %			
Corn	59.06	48.15	63.77
Soybean meal, 48% CP	26.89	27.05	32.86
Dried whey	10.00	10.00	–
Limestone	1.00	1.00	0.98
Monocalcium phosphate, 22% P	1.60	1.50	1.10
Salt	0.30	0.30	0.35
L-Lys-HCl	0.25	0.55	0.3
DL-Met	0.13	0.33	0.12
L-Thr	0.10	0.26	0.12
L-Trp	0.02	0.06	–
L-Val	0.01	0.15	–
Trace mineral premix[3]	0.15	0.15	0.15
Vitamin premix[4]	0.25	0.25	0.25
Zinc oxide	0.25	0.25	–
HP 300[5]	–	10.00	–
Total	100.00	100.00	100.00
Calculated analysis[6]			
SID AA, %			
Lys	1.10	1.60	1.22
Ile:Lys	64	57	63
Leu:Lys	133	109	129
Met:Lys	35	40	33
Met & Cys:Lys	60	59	57
Thr:Lys	65	65	63
Trp:lys	20.4	20.3	18.7
Val:Lys	70	70	69
Total Lys, %	1.23	1.77	1.37
ME, kcal/kg	3,256	3,302	3,272
NE, kcal/kg	2,427	2,407	2,407
SID Lys:ME, g/Mcal	3.38	4.84	3.73
SID Lys:NE, g/Mcal	4.57	7.44	5.16
CP, %	19.3	24.7	21.4
Ca, %	0.82	0.83	0.70
P, %	0.76	0.79	0.64
Available P, %	0.48	0.48	0.41

[1]Dietary treatments 1.10 and 1.60% SID Lys were manufactured and blended at the feed mill to create the intermediate levels of 1.20, 1.30, 1.40, and 1.50% SID Lys.

[2]SID = Standardized ileal digestible.

[3]Provided per kilogram of premix: 22 g Mn from manganese oxide; 73 g Fe from iron sulfate; 73 g Zn from zinc sulphate; 11 g Cu from copper sulfate; 198 mg I from calcium iodate; and 198 mg Se from sodium selenite.

[4]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin D3; 17,637 IU vitamin E; 3,307 mg riboflavin; 1,764 mg menadione; 11,023 mg pantothenic acid; 33,069 mg niacin; and 15.4 mg vitamin B12.

[5]Hamlet Protein, Findley, OH.

[6]NRC (2012).

Table 3. Diet composition (as-fed basis), Exp. 2[1]

Item	Formulated SID[2] Val:Lys ratio, %		Common phase
	50	85	
Ingredient, %			
Corn	62.97	62.50	63.77
Soybean meal, 48% CP	22.07	22.11	32.86
Dried whey	10.00	10.00	–
Limestone	1.00	1.00	0.98
Monocalcium phosphate, 22% P	1.65	1.65	1.10
Salt	0.30	0.30	0.35
L-Lys-HCl	0.63	0.63	0.3
DL-Met	0.27	0.27	0.12
L-Thr	0.29	0.29	0.12
L-Trp	0.08	0.08	–
L-Val	0.00	0.44	–
L-Ile	0.10	0.10	–
Trace mineral premix[3]	0.15	0.15	0.15
Vitamin premix[4]	0.25	0.25	0.25
Zinc oxide	0.25	0.25	–
Total	100.00	100.00	100.00
Calculated analysis			
SID AA, %			
Lys	1.24	1.24	1.22
Ile:Lys	57	57	63
Leu:Lys	110	110	129
Met:Lys	40	40	33
Met & Cys:Lys	60	60	57
Thr:Lys	66	66	63
Trp:Lys	20.1	20.1	18.7
Val:Lys	50	85	69
Total Lys, %	1.36	1.36	1.37
ME, kcal/kg	3,289	3,298	3,272
NE, kcal/kg	2,427	2,407	2,407
SID Lys:ME, g/Mcal	3.75	3.74	3.73
SID Lys:NE, g/Mcal	5.09	5.08	5.16
CP, %	17.6	17.9	21.4
Ca, %	0.82	0.82	0.70
P, %	0.73	0.73	0.64
Available P, %	0.49	0.49	0.41

[1]The 50 and 85% SID Val:Lys diets were manufactured and blended at the feed mill to create the intermediate Val Concentrations at 57, 63, 68, 73, and 78% of Lys.

[2]SID = Standardized ileal digestible.

[3]Provided per kilogram of premix: 22 g Mn from manganese oxide; 73 g Fe from iron sulfate; 73 g Zn from zinc sulphate; 11 g Cu from copper sulfate; 198 mg I from calcium iodate; and 198 mg Se from sodium selenite.

[4]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin D3; 17,637 IU vitamin E; 3,307 mg riboflavin; 1,764 mg menadione; 11,023 mg pantothenic acid; 33,069 mg niacin; and 15.4 mg vitamin B12.

Following base models, competing dose–response models were fitted to evaluate the functional form of ADG and G:F as a function of increased Lys dose for Exp. 1. Also, base models indicated no evidence for a Lys dose response on ADFI so dose response models were not pursued further on ADFI. In Exp. 2, competing dose response models were fitted to ADG, ADFI, and G:F. All dose models were evaluated during the experimental period (d 0 to 14) when increasing doses were fed. Competing dose–response models implemented here were the quadratic polynomial (QP), broken-line linear (BLL), or broken-line quadratic (BLQ), following Gonçalves et al. (2016a). The best-fitting dose–response model was decided using BIC, whereby a smaller BIC indicated a better fitting model. For best-fitting BLL and BLQ models, we obtained estimated breakpoints with corresponding 95% CI. When the QP model was best-fitting, the estimated SID % at maximum response and its corresponding CI was calculated as explained by Gonçalves et al. (2016a).

Base models were fitted using GLIMMIX and competing dose–response models were fitted using PROC GLIMMIX and PROC NLMIXED procedures of SAS (version 9.4; SAS Inst. Inc., Cary, NC).

RESULTS AND DISCUSSION

Results of proximate and total AA analysis for both experiments closely matched formulated values (Tables 4 and 5). For Exp. 1, Lys content consistently increased across dietary treatments. For Exp. 2, Val content increased in a step-wise manner and Lys remained constant.

Experiment 1: Validation of Lys Requirements

In Exp. 1, from d 0 to 14, ADG and G:F increased (linear; $P < 0.001$) as SID Lys increased, with no evidence for differences in ADFI across dietary treatments (Table 6). Furthermore, there was no evidence for treatment differences in ADG, ADFI, or G:F during the common period (d 14 to 28). For the overall period (d 0 to 28), ADG and G:F increased (linear; $P < 0.001$) as SID Lys increased. Similarly, BW on d 14 and 28 also increased (linear; $P < 0.001$) with increasing SID Lys.

Dose response models fitted to ADG (Fig. 1) indicated BLL and QP as competing best-fitting models (BLL BIC: 305.8 and QP BIC 306.8). For the BLL, maximum ADG was achieved with an estimated minimum of 1.45% SID Lys [95% CI: (1.31, 1.58%)]. The QP model indicated a maximum ADG above 1.60% SID Lys [95% CI: (1.47, > 1.60)], whereas 95% of maximum performance was achieved with 1.43% SID Lys.

The estimated regression equation for the BLL model was:

$$ADG = 319.66 - 176.65 \times (1.45 - \text{SID Lys}), \text{ when SID Lys} < 1.45\%$$

$$ADG = 319.66, \text{ if SID Lys} \geq 1.45\%$$

Table 4. Chemical analysis of diets (as-fed basis), Exp. 1[1]

	Formulated standardized ileal digestible Lys, %[2]					
Item	1.10	1.20	1.30	1.40	1.50	1.60
Item, %[3]						
DM	88.77	88.24	88.81	87.35	89.18	89.22
CP	20.6	20.9	21.6	23.0	23.4	24.4
Crude fiber	1.8	1.7	2.1	1.9	1.9	2.2
Ether extract	2.5	2.2	2.4	2.4	2.3	2.4
Ash	5.05	5.58	5.31	5.60	5.81	5.52
AA analysis, %[4]						
Lys	1.26	1.38	1.42	1.52	1.60	1.75
Ile	0.83	0.86	0.91	0.94	0.96	1.02
Leu	1.76	1.76	1.83	1.88	1.93	1.98
Met	0.40	0.47	0.48	0.51	0.54	0.65
Met + Cys	0.75	0.81	0.84	0.88	0.92	1.04
Thr	0.80	0.85	0.92	1.00	1.02	1.12
Trp	0.25	0.26	0.28	0.30	0.32	0.35
Val	0.91	0.95	1.03	1.08	1.12	1.22
His	0.49	0.52	0.52	0.56	0.58	0.60
Phe	0.95	0.98	1.03	1.06	1.11	1.15

[1]Diet samples were collected at the feed mill after manufacturing.

[2] SID = Standardized ileal digestible; Low (1.10% SID Lys) and high (1.60% SID Lys) diets were blended at the feed mill to create the intermediate treatments.

[3]Composite samples were submitted to Ward Laboratories (Kearney, NE) for analysis.

[4]Composite samples were submitted to Ajinomoto Heartland Inc. (Chicago, IL) for AA analysis.

Table 5. Chemical analysis of diets (as-fed basis), Exp. 2[1]

	Formulated standardized ileal digestible Val:Lys ratio, %[2]						
Item	50	57	63	68	73	78	85
Item, %[3]							
DM	89.84	90.16	90.37	90.24	90.35	90.06	90.24
CP	17.0	18.7	17.6	18.0	18.0	19.3	17.6
Crude fiber	2.0	1.7	1.7	1.7	1.2	2.0	1.8
Ether extract	2.6	2.2	2.2	2.4	2.2	2.3	2.2
Ash	5.25	5.58	5.26	5.08	5.17	5.14	5.14
AA analysis, %[4]							
Lys	1.32	1.33	1.37	1.35	1.35	1.33	1.34
Ile	0.76	0.78	0.77	0.77	0.78	0.87	0.80
Leu	1.56	1.54	1.54	1.51	1.55	1.61	1.59
Met	0.46	0.50	0.50	0.48	0.49	0.46	0.48
Met + Cys	0.73	0.77	0.77	0.74	0.78	0.75	0.77
Thr	0.92	0.89	0.92	0.89	0.90	0.94	0.96
Trp	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Val	0.78	0.84	0.88	0.92	0.99	1.04	1.10
His	0.43	0.42	0.41	0.41	0.42	0.44	0.43
Phe	0.83	0.92	0.82	0.80	0.83	0.86	0.84

[1]Treatment diet samples were collected at the feed mill after manufacturing.

[2]SID = Standardized ileal digestible; Low (50% SID Val:Lys) and high (85% SID Val:Lys) diets were blended at the feed mill to create the intermediate treatments.

[3]Composite samples were submitted to Ward Laboratories (Kearney, NE) for analysis.

[4]Composite samples were submitted to Ajinomoto Heartland Inc. (Chicago, IL) for AA analysis.

where the SID Lys level is expressed as a percentage.

The estimated regression equation for the QP model was:

$$ADG = -183.1 + 586.6 \times (SID\ Lys) - 168.8 \times (SID\ Lys)^2$$

In both cases, feed efficiency (i.e., G:F) for the experimental period (d 0 to 14) was specified to have heterogeneous variance across treatments and showed comparable (Fig. 2), had similar fit between models of BLL (BIC 627.7) and QP (BIC 629.6) forms. For the BLL, maximum G:F was achieved with an estimated minimum of 1.45% SID Lys [95% CI: (1.35, 1.54%)]. Based on the QP model, G:F was maximixed above 1.60% SID Lys [95% CI: (1.53, > 1.60)] and 95% of maximum performance was achieved with 1.41% SID Lys.

The estimated regression equation for the BLL model was:

$$G:F = 0.72657 - 0.35513 \times (1.45 - SID\ Lys),\ when\ SID\ Lys < 1.45\%$$

$$G:F = 0.72657,\ if\ SID\ Lys \geq 1.45\%$$

The estimated regression equation for the QP model was:

$$G:F = -0.3041 + (1.2081 \times SID\ Lys) - 0.3485 \times (SID\ Lys)^2$$

While the BLL and QP dose response models were competing models for both ADG and QP indicating similar, fit the estimated maximum response ranged from 1.45% SID Lys for the BLL model and > 1.60% SID Lys for the QP model. This information validated that the SID Lys requirement for 7- to 11-kg pigs in Exp. 1 was at or above 1.45% across performance responses. The estimate in Exp. 1 ensured pigs were fed a marginally Lys deficient diet (1.24% SID Lys), thus ensuring that the SID Val:Lys ratio requirement would not be underestimated.

The NRC (2012) estimates the SID Lys requirement for pigs weighing 7- to 11- kg to be 1.35% and the NRC (2012) requirement does not differentiate between different growth responses, specifically ADG and G:F. Indeed, studies have shown that the requirement can differ across response criteria. For example, Nemechek et al. (2012) determined that the SID Lys requirement for 7- to 11-kg pigs was 1.30 and 1.37% for ADG and G:F, respectively, using broken-line linear analysis. When using a quadratic broken-line analysis, the requirement increased to 1.37 and 1.54% SID

Table 6. Least square means and SEM of standardized ileal digestible (SID) Lys on nursery pig growth performance[1,2]

	Formulated SID Lys, %						Probability, $P <$	
Item	1.10	1.20	1.30	1.40	1.50	1.60	Linear	Quadratic
Treatment period (d 0 to 14)								
ADG, g	265	263	298	313	319	320	0.001	0.278
SEM	9.6	9.6	10.1	10.1	9.6	9.6		
ADFI, g	432	417	446	438	441	442	0.336	0.835
SEM	13.9	13.9	14.6	14.6	13.9	13.9		
G:F	0.616	0.631	0.670	0.714	0.725	0.729	0.001	0.249
SEM	0.0188	0.0188	0.0096	0.0096	0.0188	0.0188		
Post-treatment period (d 14 to 28)								
ADG, g	565	568	580	554	578	582	0.391	0.653
SEM	12.6	12.6	13.3	13.3	12.6	12.6		
ADFI, g	886	890	916	875	909	925	0.154	0.558
SEM	17.2	17.2	18.1	18.1	17.2	17.2		
G:F	0.637	0.639	0.633	0.634	0.636	0.630	0.578	0.954
SEM	0.0068	0.0068	0.0091	0.0091	0.0086	0.0086		
Overall (d 0 to 28)								
ADG, g	415	416	439	433	448	451	0.001	0.797
SEM	9.3	9.3	9.8	9.8	9.3	9.3		
ADFI, g	659	653	681	657	675	683	0.180	0.799
SEM	14.1	14.1	14.9	14.9	14.1	14.1		
G:F	0.630	0.636	0.645	0.661	0.665	0.661	0.001	0.401
SEM	0.0086	0.0086	0.0091	0.0091	0.0086	0.0086		
BW, kg								
d 0	6.7	6.7	6.8	6.7	6.7	6.7	0.952	0.721
SEM	0.06	0.06	0.06	0.06	0.06	0.06		
d 14	10.4	10.4	10.9	11.1	11.2	11.2	0.001	0.263
SEM	0.15	0.15	0.15	0.15	0.15	0.15		
d 28	18.3	18.3	19.0	18.9	19.3	19.3	0.001	0.758
SEM	0.27	0.27	0.29	0.29	0.27	0.27		

[1]A total of 300 nursery pigs (PIC 327 × 1,050, initially 6.7 kg BW) were used. Each mean with the SEM listed below is from 9 pens for 1.30 and 1.40 SID Lys treatments and 10 pens for the remaining treatments. All pens had 5 pigs per pen. Pigs were weaned at approximately 21 d, fed a common starter diet for 6 d post-weaning, then fed experimental diets.

[2]Experimental diets were fed from d 0 to 14 and a common diet was fed from d 14 to 28.

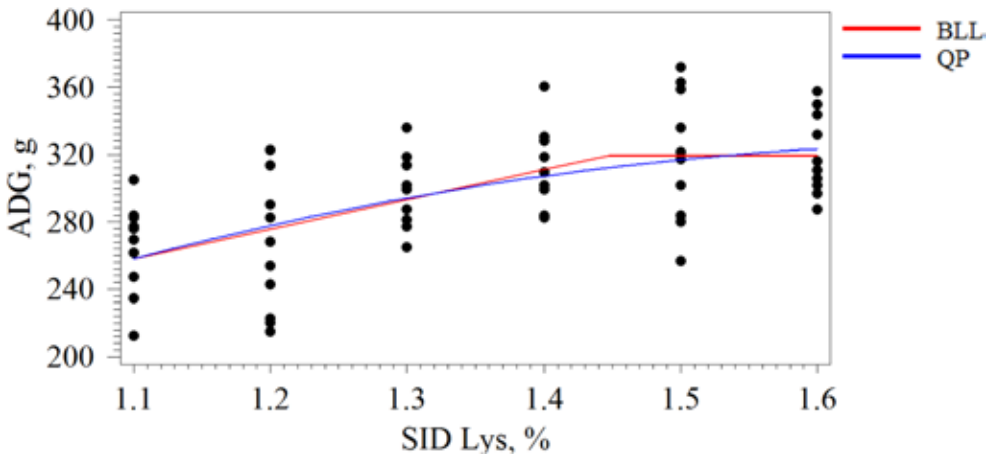

Figure 1. Nursery pig ADG dose response curves dependent on standardized ileal digestible (SID) Lys. Broken-line linear Estimated breakpoint 1.45% SID Lys, [95% CI: (1.31, 1.58)]; BIC = 305.8. QP Estimated > 1.60% SID Lys that maximized ADG [95% CI: (1.47, > 1.60)]; 95% of Maximum: 1.43% SID Lys; BIC = 306.8. A total of 300 nursery pigs (PIC 327 × 1,050, initially 6.7 kg BW) were used in a 28-d growth trial with 5 pigs per pen and 10 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 6 d post-weaning, then fed dietary treatments. Quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit to characterize the SID Lys dose response curve.

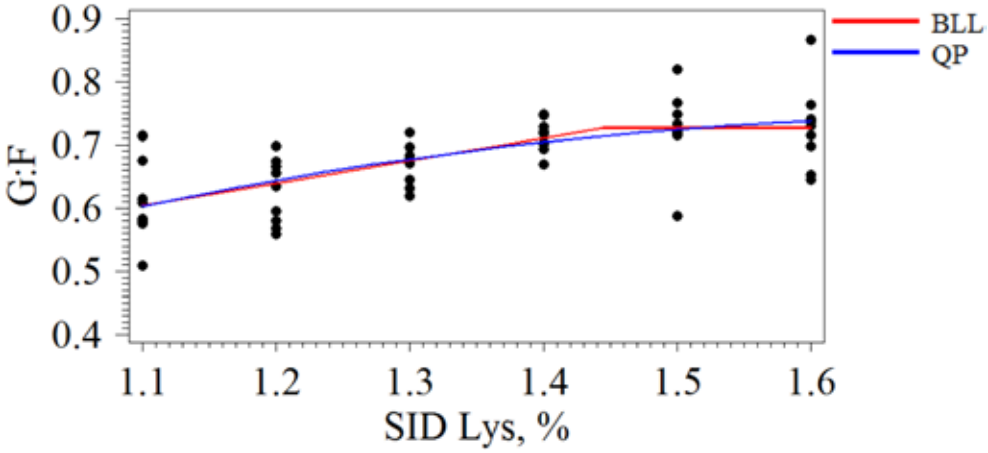

Figure 2. Nursery pig feed efficiency (G:F) dose response curves dependent on standardized ileal digestible (SID) Lys. Quadratic polynomial Estimated > 1.60% SID Lys that maximized G:F; [95% CI: (1.53, > 1.60)]; 95% of Maximum: 1.41% SID Lys; BIC = 629.6. Broken-line linear estimated breakpoint: 1.45% SID Lys; [95% CI: (1.35, 1.54)]; BIC = 627.7. A total of 300 nursery pigs (PIC 327 × 1,050, initially 6.7 kg BW) were used in a 28-d growth trial with 5 pigs per pen and 10 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 6 d post-weaning, then fed dietary treatments. Quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit to characterize the SID Lys dose response curve.

Lys for ADG and G:F, respectively. In turn, Kendall et al. (2008) concluded that the true ileal digestible Lys requirement for 11- to 27-kg pigs was 1.30% when evaluated across various response criteria. More recently, Park and Kim (2015) estimated the SID Lys requirement for 6- to 10-kg pigs to be 1.43% for ADG and ranging from 1.39 to 1.49% for G:F depending on alternative modeling strategies. These results are consistent to those of the current study where it appears the requirement may be greater than current NRC (2012) estimates. Our observed dietary SID Lys concentration at levels greater than previously estimated may be due to modern genetics with potential for increased lean tissue accretion with lower feed intake (NRC, 2012).

Experiment 2: Assessment of Val Requirement

In Exp. 2, during the experimental period (d 0 to 14), ADG, ADFI, and G:F increased (quadratic, $P < 0.039$) as SID Val:Lys ratio increased (Table 7). During the common phase (d 14 to 28), ADFI increased and G:F decreased (linear, $P < 0.028$) in pigs previously fed diets containing increasing SID Val:Lys ratio. During the overall period (d 0 to 28), ADG marginally improved (quadratic, $P = 0.089$), while ADFI increased (linear, $P = 0.006$) as SID Val:Lys ratio fed from d 0 to 14 increased. There was a quadratic ($P = 0.001$) response in BW on d 14 and marginal quadratic (linear, $P = 0.057$) response on d 28.

For ADG (Fig. 3), from d 0 to 14 when experimental diets were fed, the BLL dose response was the best fitting model. Maximum ADG was obtained with an estimated 62.9% SID Val:Lys ratio [95% CI: (52.2, 73.7%)].

The estimated regression equation for the BLL model was:

$$\text{ADG} = 247.021 - 4.383 \times (62.9 - \text{SID Val:Lys}), \text{ when SID Val:Lys} < 62.9\%$$

$$\text{ADG} = 247.021, \text{ if SID Val:Lys} \geq 62.9\%$$

whereby Val was expressed as a percentage of Lys (i.e., 50%) and initial BW was specified at its mean in the data (i.e., 6.5 kg).

For ADFI (Fig. 4), the QP functional form showed the best fit and estimated maximum feed intake at 73.7% SID Val:Lys ratio [95% CI: (61, > 85)], with 99% of maximum performance achieved with 68.0% SID Val:Lys ratio.

The estimated regression equation, considering an average initial BW of 6.5 kg, was as follows:

$$\text{ADFI} = -253.297 + 17.6999 \times (\text{SID Val:Lys}) - 0.1201 \times (\text{SID Val:Lys})^2$$

For G:F (Fig. 5), the best fitting model showed a QP functional form and yielded maximum G:F at an estimated 71.7% SID Val:Lys ratio [95% CI: (58, > 85)], with 99% of maximum performance achieved with 64.4% SID Val:Lys.

The estimated QP regression equation for G:F for a pig of average initial BW (i.e., 6.5 kg) was as follows:

$$\text{G:F} = 0.010294 + 0.017526 \times (\text{SID Val:Lys}) - 0.000122 \times (\text{SID Val:Lys})^2$$

The lowest Val:Lys ratio used in this experiment was previously confirmed to be deficient for nursery pigs weighing 7- to 11-kg by Nemechek et al. (2014).We de-

Table 7. Effects of standardized ileal digestible (SID) Val:Lys ratio on nursery pig growth performance[1,2]

	Formulated SID Val:Lys, %[3]							Probability, $P <$	
Item	50	57	63	68	73	78	85	Linear	Quadratic
Treatment period (d 0 to 14)									
ADG, g	190	221	249	249	248	251	238	0.001	0.001
SEM	5.9	11.8	11.8	11.9	11.8	11.8	11.8		
ADFI, g	331	363	394	388	403	390	386	0.012	0.030
SEM	17.1	17.1	17.1	17.2	17.1	17.1	17.1		
G:F	0.579	0.612	0.635	0.646	0.614	0.645	0.617	0.101	0.039
SEM	0.0188	0.0188	0.0188	0.0189	0.0188	0.0188	0.0188		
Post-treatment period (d 14 to 28)									
ADG, g	541	531	515	575	522	530	539	0.992	0.945
SEM	15.4	15.5	15.4	15.5	15.4	15.4	15.4		
ADFI, g	826	817	825	878	847	866	876	0.028	0.965
SEM	22.9	22.9	22.9	23.0	22.9	22.9	22.9		
G:F	0.654	0.651	0.624	0.655	0.616	0.612	0.616	0.001	0.923
SEM	0.0099	0.0099	0.0099	0.0100	0.0099	0.0099	0.0099		
Overall (d 0 to 28)									
ADG, g	366	376	382	412	385	391	389	0.067	0.089
SEM	11.0	11.0	11.0	11.0	11.0	11.0	11.0		
ADFI, g	579	590	609	633	625	628	631	0.006	0.266
SEM	17.1	17.1	17.1	17.2	17.1	17.1	17.1		
G:F	0.632	0.639	0.628	0.652	0.616	0.622	0.616	0.104	0.303
SEM	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105		
BW, kg									
d 14	9.2	9.6	10.0	10.0	10.0	10.0	9.9	0.001	0.001
SEM	0.16	0.16	0.16	0.16	0.16	0.16	0.16		
d 28	16.8	17.1	17.1	18.1	17.3	17.5	17.5	0.057	0.146
SEM	0.32	0.32	0.32	0.32	0.32	0.32	0.32		

[1]A total of 280 nursery pigs (PIC 327 × 1,050, initially 6.5 kg BW) were used in a 28-d growth trial with 5 pigs per pen and 8 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 5 d post-weaning, then fed experimental diets. Initial (d 0) BW was used as a covariate.

[2]Experimental diets were fed from d 0 to 14 and a common diet was fed from d 14 to 28.

[3]Low (50% SID Val:Lys ratio) and high (85% SID Val:Lys ratio) diets were blended upon manufacturing at the feed mill to create the 57, 63, 68, 73, and 78% SID Val:Lys ratio dietary treatments.

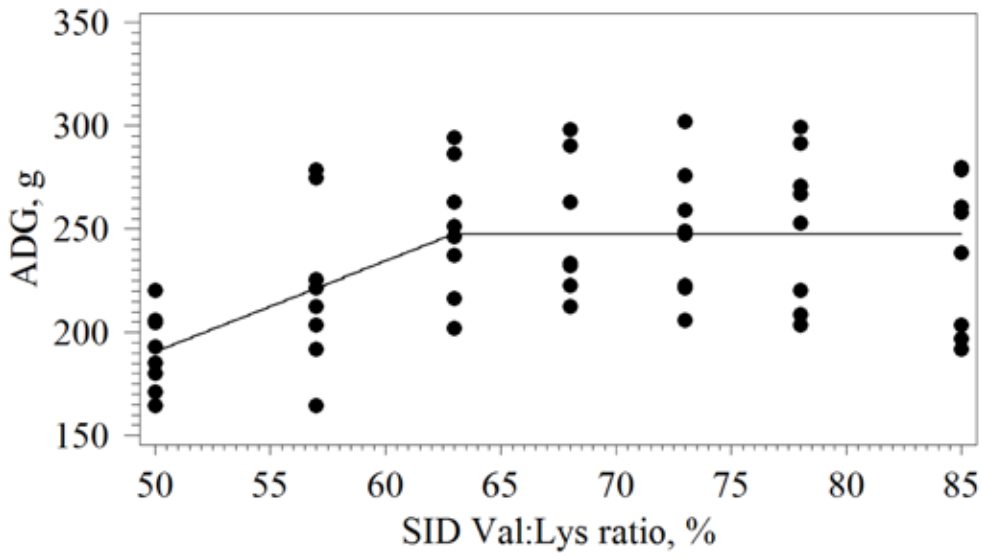

Figure 3. Nursery pig ADG dose response curve dependent on standardized ileal digestible (SID) Val:Lys ratio. Broken-line linear Estimated breakpoint: 62.9% SID Val:Lys, [95% CI: (52.2, 73.7)]. A total of 280 nursery pigs (PIC 327 × 1,050, initially 6.5 kg BW) were used in a 28-d growth trial with 5 pigs per pen and 8 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 5 d post-weaning, then fed dietary treatments. Quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit to estimate the dose response to feeding increasing SID Val:Lys.

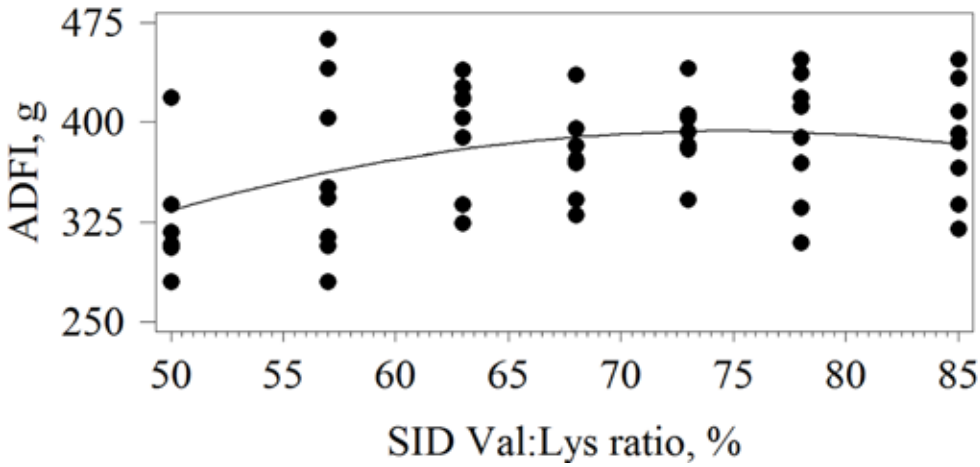

Figure 4. Nursery pig ADFI dose response curve dependent on standardized ileal digestible (SID) Val:Lys ratio. Quadratic polynomial estimated 73.7% SID Val:Lys that maximized ADFI [95% CI: (61, > 85)]; 99% of Maximum: 68.0% SID Val:Lys. A total of 280 nursery pigs (PIC 327 × 1,050, initially 6.5 kg BW) were used in a 28-d growth trial with 5 pigs per pen and 8 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 5 d post-weaning, then fed dietary treatments. Quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit to estimate the dose response to feeding increasing SID Val:Lys.

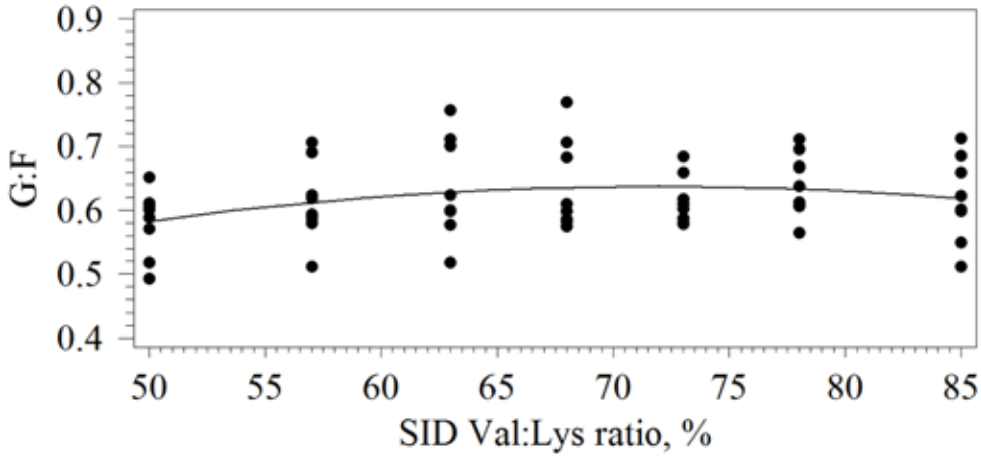

Figure 5. Nursery pig feed efficiency (G:F) dose response curve dependent on standardized ileal digestible (SID) Val:Lys ratio. Quadratic polynomial estimated 71.7% SID Val:Lys that maximized G:F [95% CI: (58, > 85)]; 99% of Maximum: 64.6% SID Val:Lys. A total of 280 nursery pigs (PIC 327 × 1,050, initially 6.5 kg BW) were used in a 28-d growth trial with 5 pigs per pen and 8 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 5 d post-weaning, then fed dietary treatments. Quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit to estimate the dose response to feeding increasing SID Val:Lys.

signed our dietary treatments to increase SID Val:Lys ratio from 50 to 85%, thus enabling dose-response modeling and estimation of requirement values at which performance can be maximized. The SID Val:Lys levels at which no further increase in performance was observed in the present experiment were 63, 74, and 72% SID Val:Lys ratio for ADG, ADFI, and G:F, respectively. Several other studies have observed similar ranges of requirement estimates across responses (Gaines et al., 2011; Nemechek et al., 2014; Soumeh et al., 2015). Specifically, Gaines et al. (2011) used single-slope broken-line methods in determining a SID Val:Lys ratio requirement estimate for 13- to 32-kg pigs and found that a ratio of 65% was sufficient for ADG and G:F. Barea et al. (2009) determined that the SID Val:Lys ratio requirement for pigs weighing approximately 12- to 25-kg post-weaned pigs was 70, 74, and 68% for ADG, ADFI, and G:F, respectively, using a linear-plateau model and 75, 81, and 68, respectively, using curvilinear-plateau models. Furthermore, Wiltafsky et al. (2009) estimated that the ideal SID Val:Lys ratio for 8- to 25-kg pigs was 65 to 67%. Nemechek et al. (2014) reported that 65% SID Val:Lys was adequate for optimal growth of 7- to 11-kg pigs. Using individually housed pigs weighing 8- to 14-kg, Soumeh et al. (2015) identified that SID Val needed to be 70% of Lys using linear and curvilinear models. Finally, the NRC (2012) suggests a 64% SID Val:Lys ratio for 7- to 11-kg nursery pigs.

An estimated range of SID Val:Lys ratio requirements is also available for heavier pigs. Waguespack et al. (2012) cite a 67 to 70% SID Val:Lys ratio requirement for 20- to 45-kg pigs. Additionally, when observing the Val:Lys ratio requirement for several weight

ranges of pigs, Liu et al. (2015) cite the requirement of SID Val at 62, 66, 67, and 68% of Lys for 26- to 46-kg, 49- to 70-kg, 71- to 92-kg, and 94- to 199-kg pigs, respectively, using broken-line linear models. However, when using quadratic models, these requirements increased to 71, 72, 73, and 72% of Lys, respectively. These models sought to maximize ADG and minimize serum urea N. Lastly, Gonçalves et al. (2016b) evaluated the Val:Lys ratio requirement in a commercial research environment (25 pigs/pen) of pigs weighing 25- to 45-kg using the same modeling techniques as used in these studies and concluded that SID Val at 67% of Lys was sufficient to capture 99% of ADG and G:F.

While our estimated requirement values agree well with NRC (2012), there seems to be a wide range of discrepancies in the Val requirement values reported in the literature (Gaines et al., 2011; Barea et al., 2009). These discrepancies in estimated requirements are to be expected given 1) the differences in underlying assumptions on the functional form of the dose-response relationship made by the models used, and 2) the physiological differences between the responses considered. For instance, modeling the results for ADG returned a much lower point of maximum return using the BLL at 63% as compared to the 73% SID Val:Lys QP maximum for ADFI models, reiterating that the suggested requirement is dependent on how each response is handled via statistical models. Thus, the ability to apply subjective performance goals (i.e., 95 or 99% of maximum performance) allows nutritionists to determine an optimal AA level that may vary depending on production system goals and economics. Providing requirements for all growth response criteria enables producers to, for instance, determine where 100% of maximum ADG can be captured, while still ensuring 99% performance on another response. This will ultimately create the best scenario to optimize economic value in setting a dietary AA level. For example, formulating SID Val to 63% of Lys captures 100% of ADG performance, while also achieving 96.6 and 98.6% of ADFI and G:F performance, respectively. Thus, these responses can be considered first individually and then jointly for a more comprehensive decision making process.

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