The effects of branched-chain amino acids on sow and litter performance[1,2]

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ABSTRACT: Sows (n = 306; PIC, Line C-19; average parity 2.1) were used to evaluate the interrelationship between valine, isoleucine, and leucine on sow and litter performance. Our objective was to determine whether the increase in litter weaning weight associated with added dietary valine is specific for valine or a result of the total branched-chain amino acid (i.e., isoleucine and[or] leucine) concentration of the diet. Eight dietary treatments (36 to 41 sows/treatment) were arranged as a 2 × 2 × 2 factorial with two levels of valine (.80 and 1.20%), isoleucine (.68 and 1.08%), and leucine (1.57 and 1.97%). This provided total branched-chain amino acid levels of 3.05, 3.45, 3.85, and 4.25%. The lowest level of each branched-chain amino acid was similar to that in a .90% lysine corn-soybean meal diet containing .15% L-lysine HCl. Amino acids other than valine, isoleucine, and leucine met or exceeded their suggested estimates relative to lysine using ratios derived from the National and Agricultural Research Councils. Average number of pigs on d 2 of lactation was 11.2, and average lactation length was 20.9 d. Number of pigs weaned ($\bar{x}$ = 10.6), sow ADFI ($\bar{x}$ = 5.85 kg), and sow weight loss ($\bar{x}$ = 4.25 kg) were not affected by dietary treatment ($P > .10$). Sow backfat loss ($P < .02$), litter weaning weight ($P < .04$), and litter weight gain from d 2 to weaning ($P > .05$) increased as dietary valine increased. Litter weight at weaning and litter weight gain were not affected by dietary isoleucine ($P > .80$) or leucine ($P > .60$). Sixteen or 17 sows per treatment (129 total) were milked manually on d 14 to 16 of lactation. Increasing dietary valine tended to increase milk urea N ($P < .07$) but did not affect milk DM, CP, fat, lactose, or ash. Increasing dietary isoleucine or leucine had no effects on milk composition. These results confirm the importance of dietary valine for increased litter weaning weight, independent of either additional dietary leucine or isoleucine.

Key Words: Sows, Branched Chain Amino Acids, Lactation

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Introduction

Recent interest in branched-chain amino acid requirements started when discrepancies were observed in amino acid ratios relative to lysine from research that was derived empirically (NRC, 1988) or factorially (ARC, 1981; Pettigrew, 1993). In previous research evaluating the valine, isoleucine, and leucine requirements for lactating sows (Haught and Speer, 1977; Rousselow et al., 1979; Rousselow and Speer, 1980), sows weaned nine or fewer pigs, and pig growth rates were 50% of current production rates. Tokach et al. (1993) reported that increasing valine from .75 to .90% in a diet containing .90% total lysine increased pig and litter weaning weights. Similarly, Richert et al. (1997a,b) found that increasing dietary valine from .75 to 1.15% also resulted in a linear improvement in litter weight gain. Research using mammary cannulation in sows (Trottier et al., 1994) has demonstrated that valine is taken up by the mammary gland in 30% greater amounts than is secreted in milk protein. In a more recent experiment, Trottier et al. (1997) reported that valine, isoleucine, and leucine were taken up in 25, 34, and 29% greater amounts than excreted in milk protein, respectively. Other studies have suggested that branched-chain amino acids may provide an important source of energy for the mammary gland (Mepham, 1982; Richert et al., 1996). Results of Richert et al. (1997a) indicated that isoleucine may spare a portion of the valine need of the mammary gland for milk synthesis. In that study, added valine increased litter weaning weights at relatively low isoleucine concentrations, but increasing isoleucine increased litter

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weaning weights regardless of valine concentrations. Therefore, the objective of our experiment was to determine whether the improved litter weaning weights observed with the increased dietary valine were specific for valine or whether other branched-chain amino acids (isoleucine or leucine) also would have this effect.

Materials and Methods

Animals. The experimental protocol used in this study was approved by the Kansas State University Institutional Animal Care and Use Committee. Primiparous and multiparous (n = 36 to 41/treatment) sows from the Kansas State University Swine Teaching and Research Center were used in this experiment. All sows were maternal line (PIC Line C-19) and were bred to terminal line (PIC Line 326) boars. During gestation, sows were housed in outside dirt lots and fed in individual stalls. Gestating sows were fed an average 1.8 kg/d with up to 2.3 kg/d provided to thin sows the first 45 d of gestation. The gestation diet was sorghum-soybean meal-based and formulated to .65% total lysine, .90% Ca, and .80% P. On d 109 of gestation, sows were moved into farrowing crates (2.1 × .6 m) with an area (2.1 × .6 m) for newborn pigs on each side of the crate in an environmentally regulated farrowing house. Temperature in the farrowing house was maintained at a minimum of 20°C, and heat lamps provided supplemental heat to the pigs. Automatic drippers supplied water to cool the sows when the temperature exceeded 30°C. All sows were fed the gestation diet until farrowing, at which time they were allotted to one of eight dietary treatments. Treatments were allotted randomly within groups of eight as sows farrowed to minimize variation in lactation length between treatments. Sows farrowed from November 1996 through December 1997. Because sows farrowed in groups of 28 to 34, three or four observations (sows) were made per treatment for each lactation group, and 12 lactation groups (blocks) were used. On d 1, pigs received 200 mg of iron (iron dextran solution), their ears were notched, and tails and navel cords were docked. Male pigs were castrated between d 5 and 8 of age. Litter size was equalized by 24 h after farrowing, and all sows began the study with at least 10 pigs.

Diet Formulation. The basal diet (Table 1) was formulated to meet or exceed amino acid requirement estimates based on ratios relative to lysine derived from NRC (1988) and ARC (1981), except for valine, isoleucine, and leucine. All other nutrients were in excess of NRC (1988) requirement estimates. The basal diet was formulated to contain .90% total lysine, .80% valine, .68% isoleucine, and 1.57% leucine. These concentrations are present in a .90% lysine corn-soybean meal diet containing .15% L-lysine HCl. Cornstarch was replaced in .40% increments with L-valine, L-isoleucine, L-leucine, or a combination of each to provide the remaining seven experimental diets. The eight dietary treatments were arranged as a 2 × 2 × 2 factorial with two levels of valine (.80 and 1.20%), isoleucine (.68 and 1.08%), and leucine (1.57 and 1.97%). This combination of treatments provided total branched-chain amino acid (**TBCAA**) levels of 3.05, 3.45, 3.85, and 4.25%. Samples of each diet were collected from each batch of feed and combined to form one composite sample per treatment. The composite sample was analyzed for CP and amino acid composition. Although most analyzed values were similar to calculated values, values for the isoleucine, leucine, and valine were less than expected when at their highest inclusions (Table 2).

Table 1. Diet composition (as-fed basis)[a]

Ingredient	Percentage
Corn	71.08
Soybean meal (46.5% CP)	20.06
Choice white grease	3.00
Monocalcium phosphate (21% P)	2.25
Limestone	1.08
Cornstarch[b]	1.20
Salt	.50
Sow add pack[c]	.25
Vitamin premix[d]	.25
Trace mineral premix[e]	.15
L-Lysine-HCl	.15
L-Threonine	.016
L-Tryptophan	.016

[a]Basal diet was formulated to 15.5% CP, .90% lysine, .80% valine, .68% isoleucine, 1.57% leucine, .90% Ca, and .80% P.
[b]Cornstarch was replaced in .40% increments with L-valine, L-isoleucine, L-leucine, or a combination of each to provide the remaining seven experimental diets.
[c]Supplied per kilogram of diet: 386 mg choline, .22 mg biotin, 11.65 mg folic acid.
[d]Supplied per kilogram of diet: 11,025 IU vitamin A, 1,103 IU vitamin D_3, 44.1 IU vitamin E, 4.4 mg menadione sodium bisulfate, 8.3 mg riboflavin, 28.7 mg pantothenic acid (as d-calcium pantothenate), 49.6 mg niacin, 165 mg choline, and .03 mg vitamin B_{12}.
[e]Supplied per kilogram of diet: 39.7 mg Mn, 165 mg Fe, 165 mg Zn, 16.5 mg Cu, .30 mg I, and .30 mg Se.

Sow Criteria. Sows were assigned to dietary treatments as they farrowed and received experimental diets within 24 h postpartum. Pigs were cross-fostered among sows irrespective of dietary treatment up to 24 h after parturition to standardize litters to at least 10 pigs with a range of 10 to 14 pigs. Sows were allowed ad libitum access to water, and feed was provided three times daily to allow ad libitum access from parturition until weaning. Creep feed was not offered to litters. Orts were collected and weighed on d 7 and 14 and at weaning to determine the sow's average daily feed intake. Backfat was measured on d 0 and at weaning using real-time ultrasound (Aloka 210; Corometrics Medical Systems, Wallingford, CT) 6 cm off the midline on both sides of the body at the last rib. Pigs and sows were weighed on d 0, 7, and 14 and at weaning. Daily amino acid intake was calculated by multiplying ADFI by the analyzed value (Table 2) for the respective amino aicds.

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Milk Criteria. Sixteen or 17 sows per treatment (129 total) were milked manually on d 14 to 16 of lactation. Sows were separated from their litters for a minimum of 30 min before milking. All sows were milked approximately 2 h after the noon feeding. Milk letdown was enhanced by infusing 10 IU of oxytocin into an ear vein of the sow. Sows were restrained with a nose snare, and milk was collected from the first two anterior productive glands on both sides of the mammary system. Each gland was milked until approximately 75 mL of milk was collected. Samples from each gland were pooled for chemical analysis and stored at 2 to 4°C. All analyses were conducted within 48 h after collection. Dry matter and ash were determined according to AOAC (1990) procedures for milk samples. Milk lactose, fat, and protein were determined using the Bentley 2000 (Bentley Instruments, Chaska, MN; AOAC, 1990). Milk urea N was determined using the Bentley ChemSpec Analyzer (Bentley Instruments; AOAC, 1990).

Blood Criteria. Sows were bled via vena cava puncture between d 17 and 20 of lactation to determine concentrations of serum urea N and plasma amino acids. Sows were given feed (1.8 kg) at 0700 and allowed 1 h to consume it, residual feed was removed, and sows were bled 3 h later at 1100. Serum urea N was determined using an auto-analyzer (Alpken Corp., Clackamas, OR) according to procedures described by Marsh et al. (1965) and Frankel et al. (1970). Plasma amino acid concentrations were determined on the third and sixth farrowing groups (seven sows/treatment). Plasma (2 mL) was mixed with 10% sulfsalicylic acid (2 mL) containing 1 m*M* norleucine as an internal standard for amino acid analysis. After cooling in an ice bath for 20 min, samples were centrifuged at 4,000 $\times g$ for 20 min. Samples were vortexed and centrifuged (13,800 $\times$ *g*). The supernatant was frozen for subsequent amino acid separation using cation exchange chromatography and measurement with fluorimetry after postcolumn *o*-phthalaldehyde derivitization (Beckman System Gold, Beckman, Palo Alto, CA).

Statistical Analysis. The GLM procedure of SAS (1988) was used to determine treatment effects. Lactation group was used as a blocking factor for all response criteria. Litter size after cross-fostering was used as a covariate for litter weights, litter weight gain, daily amino acid intake, and ADFI. Lactation length was used as a covariate for litter weaning weight, litter weight gain from d 2 to weaning, sow BW and backfat change from d 0 to weaning, ADFI, and daily amino acid intake. Initial BW and beginning backfat measurement were used as covariates for sow BW change and backfat change, respectively. Parity was a significant covariate for milk urea N, fat, lactose, and DM, but not for CP or ash. Contrasts were the following: main effects of valine, leucine, and isoleucine; the valine $\times$ leucine, valine $\times$ isoleucine, and isoleucine $\times$ leucine interactions; and the valine $\times$ isoleucine $\times$ leucine interaction. We considered *P*-values less than .05 as significant and those between .10 and .06 as trends. An additional analysis was conducted in which sows were separated according to the number of pigs weaned: 10 or fewer and 11 or greater. All values are reported as least squares means.

Results

Interactions. No valine $\times$ isoleucine $\times$ leucine interactions occurred for parity, number of pigs after fostering, number of pigs weaned, or lactation length ($P >$ .69; Table 3). Also, no three-way interactions occurred among any of the litter weights or litter weight gain

Table 2. Chemical analysis of experimental diets (as-fed basis)[a]

	Valine, %	.80				1.20			
	Isoleucine, %	.68		1.08		.68		1.08	
	Leucine, %	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97
Item, %	TBCAA, %[b]	3.05	3.45	3.45	3.85	3.45	3.85	3.85	4.25
CP		15.80	15.56	15.74	15.77	15.25	15.51	16.04	15.77
Amino acids									
Arginine		1.01	.95	.97	.94	.94	.93	.98	.93
Cysteine		.30	.31	.31	.30	.30	.29	.30	.30
Histidine		.44	.43	.43	.42	.42	.42	.43	.42
Isoleucine		.68	.70	.99	1.03	.65	.68	1.05	.99
Leucine		1.49	1.76	1.50	1.79	1.41	1.75	1.49	1.75
Lysine		.93	.90	.91	.89	.88	.87	.93	.87
Methionine		.27	.25	.28	.25	.24	.25	.26	.25
Phenylalanine		.80	.76	.78	.76	.76	.75	.78	.75
Threonine		.61	.58	.59	.56	.56	.55	.57	.55
Tryptophan		.20	.20	.20	.24	.21	.19	.20	.19
Tyrosine		.55	.50	.53	.52	.51	.50	.53	.51
Valine		.80	.84	.78	.81	1.08	1.14	1.10	1.06

[a]Values are based on analyses of one composite sample of eight batches for each diet.
[b]Total branched-chain amino acids (isoleucine + valine + leucine).

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Table 3. The effects of increasing isoleucine, leucine, and(or) valine on litter growth performance[a]

Valine, %	.80				1.20				
Isoleucine, %	.68		1.08		.68		1.08		
Leucine, %	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97	
Item TBCAA, %[b]	3.05	3.45	3.45	3.85	3.45	3.85	3.85	4.25	SE
No. of sows	40	38	39	38	38	36	36	41	—
Mean parity	2.0	2.2	2.1	2.1	2.0	2.3	2.2	2.1	.14
No. of pigs after fostering	11.1	11.2	11.3	11.1	11.3	11.2	11.1	11.0	.16
No. of pigs weaned	10.6	10.5	10.5	10.6	10.6	10.5	10.6	10.6	.13
Pig survival, %	94.9	94.0	94.5	94.4	95.0	94.2	94.9	94.7	1.17
Lactation length, d	20.5	20.9	20.7	20.8	21.0	20.8	20.8	20.6	.24
Litter wt, kg									
Day 2[c]	19.4	19.2	20.0	19.8	19.8	20.4	19.5	20.1	.43
Day 7[c]	29.8	29.2	30.3	30.2	31.1	31.3	30.0	30.8	.66
Day 14[c]	46.8	46.3	47.9	47.1	49.1	49.0	47.0	48.6	1.01
Weaning[cd]	61.6	61.5	63.0	63.1	65.0	64.7	62.7	64.9	1.31
Litter wt gain, kg									
Day 2 to 7[c]	10.4	10.0	10.4	10.4	11.3	10.9	10.5	10.7	.40
Day 2 to 14[c]	27.3	27.1	27.9	27.3	29.3	28.6	27.5	28.6	.81
Day 2 to weaning[cd]	42.3	42.3	43.0	43.3	45.2	44.3	43.3	44.9	1.12

	Statistical analysis ($P <$)						
	Interactions				Main effects		
Item	Val × Ile × Leu	Ile × Leu	Val × Leu	Val × Ile	Leu	Ile	Val
Mean parity	.89	.18	.73	.79	.30	.99	.50
No. of pigs after fostering	.78	.43	.60	.32	.57	.45	.84
No. of pigs weaned	.94	.46	.92	.85	.60	.97	.70
Pig survival	.96	.65	.96	.92	.51	.91	.77
Lactation length	.69	.65	.19	.48	.81	.95	.55
Litter weights							
Day 2	.96	.99	.18	.15	.51	.67	.29
Day 7	.92	.58	.33	.11	.88	.94	.06
Day 14	.44	.65	.31	.12	.91	.83	.05
Weaning	.54	.44	.63	.17	.62	.81	.03
Litter weight gain							
Day 2 to 7	.82	.36	.88	.27	.64	.55	.05
Day 2 to 14	.32	.57	.59	.25	.83	.61	.06
Day 2 to weaning	.47	.36	.91	.32	.76	.91	.04

[a]Litter size after cross-fostering was used as a covariate.
[b]Total branched-chain amino acids (isoleucine + valine + leucine).
[c]Parity was used as a covariate.
[d]Lactation length was used as a covariate.

measurements ($P > .44$). A valine × isoleucine × leucine interaction tended to occur for TBCAA intake ($P < .08$). Additionally, there was a valine × leucine interaction observed for sow backfat at weaning ($P < .03$). However, the actual differences in sow backfat at weaning were minimal and simply may have arisen from not blocking the sows by initial backfat between treatments.

Valine. Dietary valine had no effect on number of pigs weaned ($\bar{x} = 10.6$; Table 3) or survival rate after cross-fostering ($\bar{x} = 94.5\%$). Increasing dietary valine from 47.52 to 63.87 g/d (.80 to 1.20%, Table 4), regardless of isoleucine or leucine, increased litter weights at d 7, 14, and weaning (29.9 vs 30.8 kg, $P < .06$; 47.0 vs 48.4 kg, $P < .05$; 62.3 vs 64.3 kg, $P < .03$; respectively) and litter weight gains from d 2 to 7 (10.3 vs 10.9 kg, $P < .05$); d 2 to 14 (27.4 vs 28.5 kg, $P < .06$); and d 2 to weaning (42.8 vs 44.4 kg, $P < .04$). As dietary valine increased, valine and TBCAA intake increased ($P < .0001$; Table 4); whereas leucine and lysine intake decreased ($P < .01$). Sow ADFI ($P > .50$) and sow weight loss ($P > .30$) were not affected by dietary valine. As dietary valine increased from .80 to 1.20%, sow backfat loss increased ($P < .02$).

Isoleucine. Dietary isoleucine had no effects on number of pigs weaned or survival rate. Increasing isoleucine, regardless of valine or leucine, did not affect litter weights ($P > .67$) or litter weight gains ($P > .55$; Table 3). Sow BW ($P > .70$) and sow backfat ($P > .97$) did not change with increased dietary isoleucine. Dietary isoleucine had no effect on sow feed intake ($P > .42$; Table 4), but isoleucine and TBCAA intakes increased ($P < .0001$) as isoleucine increased in the diet. Valine intake decreased ($P < .002$) with increased dietary iso-

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leucine. A valine × isoleucine × leucine interaction ($P < .003$) was observed for isoleucine intake.

Leucine. Dietary leucine had no effects on number of pigs weaned or survival rate. Increasing leucine, regardless of valine or isoleucine, did not affect litter weights ($P > .51$) or litter weight gain ($P > .64$). Sow backfat loss ($P > .29$) was not affected by increased dietary leucine; however, sow BW loss numerically decreased ($P > .10$) as leucine intake increased. Daily leucine and TBCAA intakes ($P < .0001$) increased as dietary leucine increased and daily lysine intake decreased ($P < .0004$). This minor, but significant, decrease in daily lysine intake was brought about by lower analyzed lysine levels of the diets with increased leucine. Sow ADFI was not affected ($P > .58$).

Milk Composition. Increasing dietary valine, isoleucine, and leucine did not affect ($P > .10$) milk DM, CP, fat, ash, or lactose (Table 5). Valine was the only branched-chain amino acid that affected milk urea N, which tended to increase when dietary valine was increased ($P < .07$).

Blood Metabolites. Plasma urea N was not affected ($P > .23$) by increasing valine, isoleucine, or leucine (Table 6). Increasing dietary valine increased circulating valine concentrations ($P < .0001$). Increasing dietary leucine tended ($P < .10$) to reduce plasma lysine concentrations. A tendency for valine × leucine ($P < .07$) and a isoleucine × leucine ($P < .06$) interaction was observed for plasma valine and isoleucine concentrations. At .80% dietary valine, increasing leucine had no effect on plasma valine concentrations. However, at 1.20% dietary valine, increasing leucine resulted in decreased plasma valine concentrations. A similar response was observed for isoleucine concen-

Table 4. The effects of increasing isoleucine, leucine, and(or) valine on sow feed intake, BW, and backfat changes[a]

Valine, %	.80				1.20				
Isoleucine, %	.68		1.08		.68		1.08		
Leucine, %	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97	
Item TBCAA, %[b]	3.05	3.45	3.45	3.85	3.45	3.85	3.85	4.25	SE
Daily intake									
ADFI, kg[c]	5.95	5.80	5.90	5.87	5.94	5.86	5.74	5.86	.09
Lysine, g[c]	55.30	52.23	53.68	52.25	52.24	50.98	53.36	51.02	.80
Valine, g[c]	47.82	48.64	46.10	47.52	64.09	66.16	63.16	62.07	.90
Isoleucine, g[c]	40.76	40.50	57.83	60.55	38.60	40.45	60.40	58.15	.85
Leucine, g[c]	88.85	102.25	88.46	105.10	83.77	102.55	85.40	102.60	1.48
TBCAA, g[c]	177.42	191.38	192.38	213.18	186.47	209.15	208.96	222.80	3.12
Sow BW, kg									
Day 0	198.8	207.7	204.7	200.6	203.6	204.7	204.3	204.4	2.67
Weaning	194.5	204.3	200.5	198.4	198.2	200.9	199.0	200.7	2.95
Change[d]	–4.30	–3.44	–4.25	–2.21	–5.44	–3.83	–5.26	–3.67	1.51
Sow backfat, mm									
Day 0	15.8	14.5	15.5	14.4	14.6	15.3	15.3	16.1	.67
Weaning	14.7	13.8	14.8	13.3	13.0	13.8	13.2	15.1	.64
Change[e]	–1.12	–0.72	–0.74	–1.11	–1.65	–1.52	–2.07	–1.05	.39

	Satistical analysis ($P <$)						
	Interactions				Main effects		
Item	Val × Ile × Leu	Ile × Leu	Val × Leu	Val × Ile	Leu	Ile	Val
Daily intake							
ADFI	.73	.24	.42	.35	.58	.42	.59
Lysine	.23	.81	.69	.23	.0004	.85	.01
Valine	.14	.32	.62	.39	.21	.002	.0001
Isoleucine	.003	.64	.24	.33	.39	.0001	.40
Leucine	.25	.69	.16	.85	.0001	.32	.01
TBCAA	.08	.82	.84	.94	.0001	.0001	.0001
Sow BW							
Day 0	.29	.23	.76	.88	.60	.94	.65
Weaning	.19	.99	.99	.79	.78	.77	.63
Change	.78	.79	.94	.82	.15	.70	.35
Sow backfat							
Day 0	.94	.86	.05	.32	.67	.56	.54
Weaning	.39	.81	.03	.37	.78	.51	.37
Change	.13	.91	.32	.95	.29	.97	.02

[a]Lactation length and parity were used as covariates.
[b]Total branched-chain amino acids (isoleucine + valine + leucine).
[c]Pigs equalized after cross fostering was used as a covariate.
[d]Initial BW was used as a covariate.
[e]Beginning backfat measurement was used as a covariate.

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Table 5. The effects of valine, isoleucine, and leucine on milk composition[a]

	Valine, %	.80				1.20				
	Isoleucine, %	.68		1.08		.68		1.08		
	Leucine, %	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97	
Item	TBCAA, %[b]	3.05	3.45	3.45	3.85	3.45	3.85	3.85	4.25	SE
Milk urea N, mg/dL[c]		49.23	47.65	48.74	50.11	52.26	51.61	50.44	50.76	1.84
DM, %[c]		16.76	17.06	16.91	16.67	16.63	16.84	16.76	16.97	.23
CP, %[c]		4.60	4.58	4.49	4.55	4.55	4.47	4.47	4.51	.08
Fat, %[c]		5.12	5.40	5.31	5.21	4.95	5.23	5.37	5.43	.18
Lactose, %[c]		5.82	5.75	5.87	5.87	5.89	5.89	5.83	5.87	.06
Ash, %[c]		.72	.70	.69	.71	.70	.72	.69	.71	.02

	Statistical analysis ($P <$)						
	Interactions				Main effects		
Item	Val × Ile × Leu	Ile × Leu	Val × Leu	Val × Ile	Leu	Ile	Val
Milk urea N	.70	.44	.98	.37	.92	.89	.07
DM	.39	.42	.58	.44	.46	.96	.76
CP	.86	.37	.72	.63	.98	.39	.35
Fat	.75	.23	.75	.22	.30	.22	.91
Lactose	.89	.51	.46	.13	.79	.54	.31
Ash	.39	.53	.49	.91	.38	.41	.98

[a]Values represent the means of 16 sows/treatment.
[b]Total branched-chain amino acids (isoleucine + valine + leucine).
[c]Parity was used as a covariate.

trations. At .65% isoleucine, increasing leucine had no effect on plasma isoleucine, but at 1.08% dietary isoleucine, increasing leucine decreased plasma isoleucine concentrations.

Discussion

Increasing dietary valine from .80% to 1.20% increased litter weaning weight by 2 kg and litter weight gain from d 2 to weaning by 1.7 kg, independent of dietary isoleucine and leucine levels (Table 3). This suggests that increasing dietary valine increased milk production as measured by litter weaning weights with no influence of dietary leucine or isoleucine. This response to valine has been observed in previous experiments conducted with high producing sows. When the valine level was increased from .75 to 1.15% in diets formulated to .90% lysine, litter weaning weights increased linearly up to 3.7 kg and litter weight gain increased 3.4 kg (Richert et al., 1996). In our experiment, we did not observe any change in sow weight or ADFI when additional valine was added. We did observe an increase in last-rib backfat loss, but it was minimal (1.5 mm). Increased backfat loss would be expected if ADFI remained constant and milk production, as measured by increased litter weaning weights, increased. Richert et al. (1996) observed the same lack of responses for sow weight change and ADFI, but there was no change in last-rib backfat.

In earlier work, Rousselow and Speer (1980) determined that the valine requirement was at least .53% when sows were fed .53% lysine based on N retention. However, a further increase in litter performance occurred at .68% valine, so the optimal valine:lysine ratio could be greater than 1:1. Richert et al. (1996) reported that the optimal valine:lysine ratio was at least 127% of lysine for sows weaning litters, twofold heavier than reported by Rousselow and Speer (1980). In our experiment, in which only two valine:lysine ratios (89 and 133%) were evaluated, an increase in litter weaning weight and litter weight gain was observed when the ratio was 133%. The use of an optimum valine:lysine ratio is important in the formulation of sow lactation diets.

In current production, sows require higher levels of lysine to increase litter growth rate (Johnston et al., 1993). The control diets in the trials done by Richert et al. (1996) and in our trial provided similar branched-chain amino acid:lysine ratios as a corn-soybean meal diet with .15% L-lysine HCl. Valine deficiencies limit the response of litter weight gain when .15% L-lysine HCl is used in corn-soybean meal sow lactation diets (Tokach et al., 1993). Touchette et al. (1998) concluded that up to .075% L-lysine HCl can be used in lactating sow diets before another amino acid (valine) becomes limiting. Richert et al. (1997b) evaluated three valine:lysine ratios (80, 100, or 120%) in sow lactation diets to determine whether the response to valine changes as dietary lysine increases. Litter weaning weights and litter weight gains increased with increasing lysine, and litter weight gain tended to increase with increasing valine, although the valine response was not significant. Sows nursing 10 or more pigs were responsible for most of the lysine and valine responses. The optimal valine:lysine ratio of sows nursing 10 or more in the experiment of Richert et al. (1997b) was

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found to be at least 120%, and increased levels of valine had no effect on sow ADFI or weight loss.

In previous studies, we have observed a greater increase in litter weaning weight in sows nursing litters with 10 or more pigs than those only nursing nine pigs or fewer (Tokach et al., 1993; Richert et al., 1997b). In the present study, we also evaluated responses to valine, isoleucine, and leucine additions based on number of pigs per litter on d 2 of lactation. However, unlike the differential responses observed by Tokach et al. (1993) and Richert et al. (1997b), we observed virtually no differences in the response to branched-chain amino acid supplementation based on sow productivity.

Guan et al. (1998) estimated lysine, threonine, and valine requirements of lactating sows by plasma arteriovenous differences of free plasma amino acids across the mammary gland and determined that the lysine and valine requirements were 40.9 and 46.3 g/d, respectively, giving a valine:lysine ratio of 113%. This ratio is higher than the current NRC (1998) recommendation of 85%. Valine seems to be the reason that experiments using low-protein diets fortified with synthetic amino acids have not been able to observe similar performance as those fed corn-soybean meal control diets (Tokach et al., 1993). However, other researchers have found no influence of increased dietary valine. For example, Feng et al. (1996) saw no response

Table 6. The effects of valine, isoleucine, and leucine on plasma urea N and amino acid concentrations[a]

Valine, %	.80				1.20				
Isoleucine, %	.68		1.08		.68		1.08		
Leucine, %	1.57	1.97	1.57	1.97	1.57	1.97	1.57	1.97	
Item TBCAA, %[b]	3.05	3.45	3.45	3.85	3.45	3.85	3.85	4.25	SE
Urea N, mg/dL	6.27	5.83	6.58	6.52	7.41	6.86	6.55	6.34	.53
Amino acids, mmol/L									
Alanine	.512	.528	.623	.500	.585	.499	.506	.535	.038
Arginine	.128	.123	.123	.128	.136	.139	.154	.129	.016
Aspartate	.037	.041	.042	.040	.040	.039	.038	.043	.003
Glutamate	.261	.292	.285	.355	.250	.260	.247	.288	.048
Glutamine	.256	.296	.318	.291	.282	.244	.274	.326	.028
Histidine	.083	.088	.090	.086	.084	.091	.082	.093	.006
Isoleucine	.097	.076	.183	.131	.093	.089	.200	.150	.014
Leucine	.168	.249	.175	.186	.184	.219	.163	.202	.018
Lysine	.135	.108	.130	.130	.154	.105	.123	.108	.019
Methionine	.024	.025	.023	.025	.028	.025	.026	.023	.002
Phenylalanine	.068	.069	.075	.069	.080	.068	.071	.070	.006
Threonine	.102	.098	.105	.104	.118	.094	.096	.097	.010
Tryptophan	.058	.054	.058	.060	.062	.058	.057	.061	.005
Tyrosine	.096	.110	.102	.108	.117	.094	.095	.085	.009
Valine	.184	.183	.205	.203	.429	.348	.433	.320	.037

	Statistical analysis ($P <$)						
	Interactions				Main effects		
Item	Val × Ile × Leu	Ile × Leu	Val × Leu	Val × Ile	Leu	Ile	Val
Urea N	.99	.64	.87	.12	.40	.80	.20
Amino acids							
Alanine	.02	.81	.65	.25	.13	.72	.73
Arginine	.42	.71	.63	.85	.64	.86	.24
Aspartate	.11	.95	.53	.88	.44	.36	.98
Glutamate	.96	.62	.71	.65	.27	.41	.28
Glutamine	.03	.84	.71	.53	.98	.31	.94
Histidine	.41	.70	.35	.75	.26	.72	.91
Isoleucine	.70	.06	.64	.47	.002	.0001	.25
Leucine	.15	.20	.72	.74	.002	.07	.86
Lysine	.89	.25	.49	.39	.10	.84	.83
Methionine	.89	.84	.15	.61	.76	.48	.60
Phenylalanine	.30	.78	.60	.42	.27	.99	.61
Threonine	.48	.34	.58	.33	.35	.72	.89
Tryptophan	.91	.36	.88	.56	.87	.82	.54
Tyrosine	.42	.82	.03	.15	.63	.28	.32
Valine	.77	.75	.07	.53	.06	.87	.0001

[a]Means represent seven sows/treatment for urea N and for amino acid levels. Sows were bled on d 17 to 20 of lactation.

[b]Total branched-chain amino acids (isoleucine + valine + leucine).

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when they increased the valine:lysine ratio from 82 to 92%. Recently, Boyd et al. (1999) reported a lack of response to increasing dietary valine from 90 to 126% of lysine. However, the high feed intake of sows in that study may have mitigated the response to added valine.

Richert et al. (1997a) reported that isoleucine had a direct effect on litter weaning weight. Litter weaning weight increased as isoleucine increased from .50 to 1.20% in the diet, with the greatest increase observed at .85% dietary isoleucine and 1.07% valine. Sow ADFI was not affected by increased isoleucine levels in that trial or in our experiment. Sow backfat loss and sow weight loss were increased by increased dietary isoleucine in the previous study. In contrast, we did not observe an overall benefit in litter growth or sow performance when isoleucine was added to the diet. The greatest response in litter weaning weight noted in the previous study was from increasing isoleucine from .50 to .85%. The isoleucine level (.85%) yielding the greatest response was intermediate to our levels of .68 and 1.08%. Our data do not necessarily refute those of Richert et al. (1997a), because we observed numerical increases in litter weaning weight and litter weight gain when sows were fed the low level of valine (.80%) and the high level of isoleucine (1.08%), independent of the leucine level. In a study conducted by Haught and Speer (1977) to evaluate the isoleucine requirement, the optimal level of isoleucine was .39% (71% of lysine) for sows nursing nine pigs and fed a dextrose-oat groat based diet containing .55% lysine and .47% valine. In comparison, sows in our experiment weaned 10.6 pigs with corresponding isoleucine:lysine ratios of 76 and 120. The ideal isoleucine:lysine ratio in the trial conducted by Richert et al. (1997a) was determined to be 94%, which is approximately .2 percentage unit greater than requirement estimates for lactating sows by the NRC (1998) and the ARC (1981). Further research is required to determine the ideal isoleucine:lysine ratio; however, the response to valine when isoleucine was not present in the diet in our experiment and the study by Richert et al. (1997a) indicates that valine is more critical for litter weight.

The only published research evaluating the leucine requirement of the lactating sow was that conducted by Rousselow et al. (1979). Diets in two trials contained .58% lysine with .39% valine, and .36% isoleucine. Sow lactation weight change and pig weight gain were not influenced by dietary leucine level. Because plasma urea N was minimized at .46% leucine, they concluded that this was the requirement for the lactating sow, which was the basis for the NRC (1988) requirement estimate of .48%. In the current experiment, sow lactation weight change and litter weight gain were not influenced by increased levels of leucine. However, our leucine levels were considerably higher (1.57 and 1.97%) than those of Rousselow et al. (1979; .44 to 1.24% in Trial 1 and .26 to 1.06 in Trial 2). High producing sows may require higher dietary leucine than the sows evaluated in the previous study; however, diets formulated to meet conventional lysine requirements do not seem to be deficient in leucine.

Previous data (Richert et al., 1997a) suggested that a TBCAA requirement exists for lactating sows; however, only isoleucine and valine concentrations were changed. The present study incorporated leucine into the assessment of branched-chain amino acid requirements. We found tendency for a numeric increase in litter weight with increased levels of TBCAA, but this was due primarily to the increased valine in the diets. Only one other study that evaluated the supplementation of all three branched-chain amino acids has been reported (Trottier and Easter, 1995). Sows were fed .68% lysine, .75% valine, .60% isoleucine, and 1.46% leucine or a diet containing supplemental branched-chain amino acids to achieve valine, isoleucine, and leucine levels of 1.33, 1.14, and 1.90%, respectively, to give a TBCAA level of 4.37%. This trial actually was designed to determine the impact of the BCAA:tryptophan ratio on feed intake. Sows weaned 8.1 pigs, and additions of branched-chain amino acids had no benefit on litter performance. The low lysine level fed in the experiment may have limited the response.

Research using mammary vein cannulation in sows (Trottier et al., 1994) and dairy cows (Hanigan et al., 1991) has shown that isoleucine and valine are taken up by the mammary gland in amounts 30 to 80% greater than their outputs in milk protein. Another study by Trottier et al. (1997) showed that the uptakes of valine, isoleucine, and leucine exceed their quantitative excretion in milk. Amino acids that seem to be taken up in excess of their output in milk may be biologically required by the mammary gland (Trottier et al., 1997). The branched-chain amino acids seem to serve a purpose other than just synthesizing milk protein. Isoleucine can be metabolized to succinyl-CoA and acetyl-CoA, whereas valine can be metabolized only to succinyl-CoA. Therefore, both isoleucine and valine possibly could be oxidized, hence an energy source in the mammary gland. However, because isoleucine did not elicit the same litter growth response as valine, preferential metabolism of valine may occur.

Milk composition was not altered when valine was added to the diet. Therefore, the increase in litter weaning weight could be a result of increased milk yield. Richert et al. (1997a) also saw minimal effect of increased valine on milk protein, but they reported that valine increased milk fat and DM concentrations. Rousselow and Speer (1980) found that as dietary valine increased, milk protein increased. Perhaps the dietary valine levels used in our study were already high enough to maximize milk protein concentration.

Contrary to results of the current experiment, Richert et al. (1997a) reported increased milk fat, CP, and DM concentrations with increased isoleucine in the diet. These contrasts may be due to the difference in amino acid levels fed in each experiment. Rousselow et al. (1979) found mixed results after conducting two

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trials where leucine was added to the diet. In the first trial, milk production responded irregularly, but total solids and milk protein increased quadratically. In the second trial, milk production was maximized at .66% leucine, with total solids and milk protein failing to respond to treatments. Leucine had no effect on any of the milk criteria in our experiment, suggesting that the concentrations provided by a corn-soybean meal diet with .15% L-lysine HCl are adequate to maximize litter weaning weights.

Amino acid requirements often have been based on plasma urea N concentrations. As the amino acid requirement is met, plasma urea N will decrease to its lowest observed level and then increase as the requirement is exceeded. As dietary valine increased across the levels of leucine and isoleucine, no differences were found in plasma urea N among treatments. This indicates little change in muscle catabolism, which was verified by small changes in sow BW. In other research, the serum urea N concentrations increased linearly with increasing dietary valine (Richert et al., 1996). When both valine and isoleucine were added, plasma urea N was not affected by increasing dietary valine (Richert et al., 1997a). However, increasing valine in the diet did increase milk urea N in our experiment. If valine is being used as an energy source, it would be catabolized through the TCA cycle via succinyl-CoA, resulting in additional output or yield of milk with no change in composition. If valine is being oxidized by the mammary gland, this might explain the increased milk urea N observed.

As expected, plasma valine, isoleucine, and leucine levels increased as each amino acid increased in the diet. The trends for valine × leucine and isoleucine × leucine interactions may indicate that the leucine requirement may have been very close to our basal concentration of 1.57% of the diet. We base this hypothesis on the numerical ($P = .15$) reduction in weight loss of sows fed diets with added leucine. We speculate that, at 1.57% dietary leucine, more body protein may have had to be mobilized to meet the sow's leucine requirement. However, at 1.97% dietary leucine, sows lost less BW; therefore, the lower plasma lysine, valine, and leucine concentrations may reflect fewer amino acids provided by muscle catabolism. Tokach et al. (1992) fed sows a corn-soybean meal lactation diet or a low-protein diet fortified with crystalline lysine, valine, threonine, tryptophan, and methionine. Sows fed the low-protein amino acid-fortified diets had litter weaning weights similar to those fed the corn-soybean meal diet but lost significantly greater weight during lactation. This increase in sow weight loss was also observed by Touchette et al. (1998) in sows fed a low-protein diet fortified with crystalline lysine, threonine, tryptophan, and methionine compared with those fed a corn-soybean meal diet. In that study, daily litter growth rate was also reduced, likely because valine was not added to the diet. Perhaps the increased BW loss observed by Tokach et al. (1992) and Touchette et al. (1998) was an attempt to meet the sow's leucine requirement. These data, like those of King et al. (1993), may suggest that, for an amino acid, there is one requirement for maximum milk production and a second, higher requirement for minimizing sow weight loss. Studies titrating leucine over a wide range of dietary concentrations are needed to confirm this hypothesis.

In conclusion, we determined that isoleucine did not elicit a sparing effect as seen in previous experiments. Leucine also seemed to have no impact on sow or litter performance. Therefore, the improved litter weaning weights observed in this experiment were due specifically to dietary valine and not dietary isoleucine or leucine.

Implications

The valine requirement of high-producing lactating sows may be greater than current estimates of the National Research Council and Agricultural Research Council. The increases in litter weights and litter weight gain with increased valine, independent of isoleucine and leucine, indicate that the response is due entirely to valine and not to the amounts of total branched-chain amino acids in the diet. Leucine and isoleucine did not spare the requirement for valine in lactating sows. Thus, the importance of valine for milk production must be considered when formulating diets.

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