Evaluating nutritional strategies in the sow transition period to improve sow and litter performance, colostrum yield, and piglet survivability

by

Kiah Marie Gourley

B.S., Kansas State University, 2015
M.S., Kansas State University, 2017

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry
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Abstract

Three experiments using a total of 1,325 sows were used to determine the impact of different sow feeding strategies on sow and litter performance. Experiment 1 determined the optimal soybean meal concentration in lactating sow diets using three levels of increasing dietary soybean meal (25, 30, or 35% of total diet). Increasing soybean meal concentration increased sow BW loss and tended to increase sow backfat loss from farrowing to weaning. Sow average daily feed intake (ADFI) decreased linearly as soybean meal concentration increased. Despite the linear response in ADFI, the greatest decrease was observed as soybean meal concentration increased from 30 to 35% of the diet. There was no evidence for difference in wean to estrus interval, or litter performance between dietary treatments. Sow serum urea nitrogen concentrations taken on d 14 of lactation increased as soybean meal concentration increased. Experiment 2 evaluated the duration of feeding increased Lys and energy prior to farrowing on sow and litter performance, piglet survival and colostrum quality in a commercial sow farm. Sows were fed 1 of 3 dietary regimens starting on d 107 of gestation: 1) Control: 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 2.7 kg/d lactation feed (28 g SID Lys and 9.4 Mcal ME) until parturition; 2) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition; or 3) 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition. Increasing the duration of feeding additional Lys and ME increased sow weight and backfat gain from d 106 to 113. Average total born and born alive piglet birth weight (BiWt) was greater in gilts fed 3.8 kg/d lactation diet starting on d 107 or 113 vs. control, with no difference in piglet BiWt in sows or weaning weight in gilts and sows. Piglet mortality after cross-foster to weaning was decreased in sows fed 3.8 kg/d lactation diet starting on d 113 vs.

control or increased lactation diet starting on d 107, but not in gilts. Litter gain from cross-foster to weaning was decreased in gilts fed 3.8 kg/d lactation diet starting on d 107 compared to control, with no evidence for difference in sows. Colostrum immunoglobulin G was increased in gilts and sows fed 3.8 kg/d of the lactation diet starting on d 113 compared to control. There was no evidence dietary regimen influenced piglet colostrum intake or colostrum yield, or subsequent reproductive performance. Experiment 3 evaluated the effects of timing and size of meals before farrowing on sow and litter performance under commercial conditions. Sows were fed 1 of 3 feeding management strategies until farrowing: 1) 2.7 kg lactation diet (1.15% standardized ileal digestible lysine and 2,153 Kcal/kg net energy) once daily at 0700 h; 2) 4 daily meals of 0.67 kg (0100 h, 0700 h, 1300 h, 1900 h); 3) ad libitum lactation diet and encouraged to consume feed at 0100 h, 0700 h, 1300 h, and 1900 h. Feeding sows ad libitum before farrowing tended to reduce sow body weight loss and reduce backfat loss from entry into the farrowing house until weaning compared to sows fed 4 daily meals, with sows fed once daily intermediate. Litter gain from 24 h to weaning tended to be greater in sows fed ad libitum or 4 times daily prior to farrowing compared to sows fed one meal. Piglet weaning weight increased in sows fed ad libitum before farrowing, compared to those fed one meal, with those fed 4 times daily intermediate. There was no evidence for difference in farrowing duration, stillborn rate, colostrum yield, or 24 h piglet survival regardless of treatment. However, from 24 h after farrowing to weaning, sows fed one daily meal prior to farrowing had an increased percentage of fall-behind pigs compared to sows fed ad libitum, and increased preweaning mortality compared to sows fed four daily meals, resulting in reduced weaned percentage compared to sows fed four daily meals. There was no difference in subsequent reproductive performance regardless of treatment.

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Each one of you has impacted my life in a profound way, and I am blessed to have the best team of supporters. I love you all.

“Success is secondary to impact. Success is a list of things you win, gain and attain; it may pass, it may remain. Impact is the test. The hearts, minds, and lives you touch, enhance, and forever change”- Anonymous

Dedication

This dissertation is dedicated to my mom and dad, Joyce and Mark.

Chapter 1 - Effects of soybean meal concentration in lactating sow diets on sow and litter performance, and blood criteria

ABSTRACT

A total of 131 sows (Line 241; DNA, Columbus, NE) were used in a study to evaluate the effect of increasing soybean meal concentration in lactating sow diets on sow and litter performance. Sows were blocked by body weight (BW) within parity on d 112 of gestation and allotted to 1 of 3 treatments of increasing dietary soybean meal (25, 30, or 35% of total diet). Diets were formulated to 1.05% standardized ileal digestible Lys with L-Lys HCl decreasing as soybean meal increased. All other amino acids and nutrients were formulated to meet nutrient requirement recommendations (NRC, 2012). Diets were fed from d 112 of gestation until weaning (d 20 ± 2). Litters were cross-fostered up to 48 h after farrowing to equalize litter size. Increasing soybean meal concentration increased (linear, $P = 0.017$) sow BW loss and tended to increase (quadratic, $P = 0.052$) sow backfat loss from farrowing to weaning. Sow average daily feed intake from d 0 to 7 was similar ($P > 0.10$) across dietary treatments. However, from d 7 to 14, 14 to weaning, and overall, average daily feed intake decreased (linear, $P = 0.01$) as soybean meal concentration increased. Despite the linear response in ADFI, the greatest decrease was observed as soybean meal concentration increased from 30 to 35% of the diet. There was no evidence for difference ($P > 0.10$) in wean to estrus interval, litter size, litter weight, or litter weight gain between dietary treatments. Sow serum urea nitrogen concentrations taken on d 14 of lactation increased (linear, $P = 0.001$) as soybean meal concentration increased. There was no difference ($P > 0.05$) for sow creatinine concentration, regardless of dietary treatment, suggesting the increased urea nitrogen was a reflection of the increased dietary crude protein as opposed to increased protein catabolism. In summary, sow feed intake decreased, and weight loss increased as soybean meal concentration of the diet increased, with the greatest decrease observed at 35% of the total diet. Although there were no differences in litter performance, it appeared that 35% soybean meal in the lactation diet negatively affected feed intake.

INTRODUCTION

Encouraging sow feed intake during lactation is one of the most critical factors in achieving maximum productivity in the farrowing house. Increased feed intake is associated with improved litter performance and sow reproductive performance (Koketsu et al., 1996). It is important that diet ingredient composition does not negatively affect lactation feed intake. A previous study (Yang et al., 2000a) observed a decrease in lactation average daily feed intake (**ADFI**) as total Lys increased from 0.60 to 1.60%. While the researchers hypothesized the decrease in intake was due to elevated serum urea nitrogen levels and varying branch chain amino acid ratios across their experimental diets, the soybean meal concentration also increased from 12.6 to 48.5% of the diet. A more recent study (Gourley et al., 2017) observed a decrease in feed intake when soybean meal increased above 29% of the total diet as total Lys concentration was increased.

To meet the standardized ileal digestible Lys requirement of the high-producing sow, both soybean meal and crystalline Lys are typically added to the diet; however, the question remains whether a maximum dietary concentration of soybean meal that should be considered? To our knowledge, there is no previous research that has evaluated this question, while keeping Lys constant in dietary treatments. Therefore, the objective of the current study was to determine if the soybean meal level in lactation diets affects sow performance and feed intake.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The experiment was conducted at the Kansas State University Swine Teaching and Research Center (Manhattan, KS).

A total of 131 sows (Line 241; DNA, Columbus, NE) and litters (241 × 600, DNA Genetics, Columbus, NE) were used across five batch farrowing groups (February to April, and July to September 2018). Sows were individually housed in an environmentally controlled and mechanically ventilated barn. Each farrowing crate was equipped with a nipple waterer and electronic feeding system (Gestal Solo Feeder, Jyga Technologies, St-Lambert-de-Lauzon, Quebec, Canada). On d 112 of gestation, sows were weighed using a scale and moved into the farrowing house. Females were blocked by initial body weight (**BW**) within parity and allotted to 1 of the 3 dietary treatments within farrowing group. Dietary treatments were corn-soybean meal-based and consisted of three concentrations of soybean meal (25, 30, or 35% of the diet; Table 1). L-Lys HCl was decreased in the diets as soybean meal increased in order to formulate all diets to 1.05% standardized ileal digestible Lys. Other feed-grade amino acids (Met, Thr, Trp, Val) were added as needed to maintain a similar ratio to Lys. All other nutrients met or exceeded the NRC (2012) requirement estimates. Gestation diets fed prior to the study contained 0.56% SID Lys, and 15% soybean meal. Sows received 2 kg/d of the gestation diet until entry into the farrowing house (d 112).

Diets were manufactured at the Kansas State University O.H. Kruse Feed Mill in Manhattan, KS. A new batch of each treatment diet was manufactured for each farrowing group and packaged in 22.7 kg bags. During bagging, feed samples were collected from every fifth bag, pooled, and used for nutrient analysis.

From d 112 of gestation until farrowing (approximately d 115), sows were fed 2.47 kg/d of their respective treatment diets. Postpartum, sows were allowed *ad libitum* access to feed. Feed was weighed and added to a bin in front of each farrowing crate and used to feed each respective sow. Feed intake was recorded by weighing the amount of feed placed in the feeder and the amount remaining in the bin every 7 d until weaning. Sow BW and backfat depth (measured at the P2 position; Renco Lean Meter, S.E.C. Repro Inc., Quebec, Canada) were recorded at 24 h after farrowing and at weaning (d d 20 ± 2). Within 48 h postpartum, piglets were processed and cross-fostered, regardless of dietary treatment, in an attempt to equalize litter size (minimum of 12 pigs per litter). Litters were weighed on d 2, 7, 14 and at weaning. Litter average daily gain was calculated as: [(litter weaning weight – d 2 litter weight)/ (days from d 2 to weaning)]. Pre-weaning mortality was calculated as the number of pigs weaned per sow divided by the number of pigs on d 2.

On d 14 of lactation, sows were fasted for 10 h and 10 mL of blood was collected via jugular venipuncture. Blood samples were centrifuged, serum was collected and then stored at -80°C until analysis. At weaning, sows were moved to a breeding barn, individually housed, and checked daily for signs of estrus using a boar. The wean-to estrus interval (**WEI**) was determined as the number of days between weaning and when sows were first observed to show a positive response to the back-pressure test.

Calculations for maternal empty body weight (**EBW**), body lipid (**BL**) and body protein (**BP**) at farrowing and weaning were made using equations 8-49, 8-50, and 8-51 from NRC (2012), as follows:

Maternal EBW (kg) = 0.96 × maternal BW

Maternal BL (kg) = -26.4+ 0.221 × maternal EBW +1.331 × P2 backfat

Maternal BP (kg) = 2.28 + 0.178 × maternal EBW -0.333 × P2 backfat

where backfat is measured in mm, and BW is in kg.

Chemical Analysis

Five samples (1 pooled sample per farrowing batch) per dietary treatment were sent to a commercial laboratory and analyzed in duplicate (Ward Laboratories, Kearney, NE) for CP (method 990.03; AOAC, 2006), Ca and P (method 985.01; AOAC, 1990). Serum samples were analyzed in duplicate for serum urea nitrogen (Urea Nitrogen Colorimetric Detection Kit; Arbor Assays; Ann Arbor, MI) and creatinine (Creatinine Colorimetric Assay Kit; Cayman Chemical; Ann Arbor, MI).

Statistical Analysis

Data were analyzed using generalized linear mixed models where dietary treatment was a fixed effect, with the random effects of farrowing group and block. Statistical models were fitted using the GLIMMIX procedure of SAS (Version 9.4, SAS Institute, Inc. Cary, NC). Pre-planned linear and quadratic contrast statements were used to evaluate increasing soybean meal concentrations.

Sow ADFI, BW, backfat depth, litter weight, litter gain, lactation length, maternal empty BW, maternal BL and BP, serum urea nitrogen and creatinine were evaluated assuming a normal distribution of the response variable. Litter weight on d 2 was used as a covariate for d 7, 14, and weaning litter weights, and litter weight gain to improve the fit of the model. In these cases, assumptions for normal distribution were checked using standardized residuals.

Litter counts and the wean-to-estrus interval were fit using a negative binomial distribution. Piglet survivability was fit using a binomial distribution. Statistical models were implemented using the GLIMMIX procedure of SAS (Version 9.4, SAS Institute, Inc., Cary, NC). All results were considered significant at $P \leq 0.05$, and marginally significant at $0.05 \leq P \leq 0.10$.

RESULTS

Chemical analysis of CP, Ca, and P were similar to formulated values (Table 2). There was no evidence for difference ($P < 0.10$) among treatments in initial BW or backfat depth measured after farrowing (Table 3), which validates the randomization of treatments. Increasing soybean meal concentration increased (linear, $P = 0.017$) sow BW loss and tended to increase (quadratic, $P = 0.052$) sow backfat loss from farrowing to weaning. Sow average daily feed intake from d 0 to 7 was similar ($P > 0.05$) across treatments. However, from d 7 to 14, 14 to weaning, and overall, ADFI decreased (linear, $P < 0.001$) as dietary soybean meal concentration increased. Additionally, overall ADFI appeared to be more variable as soybean meal concentration increased in the diet (Figure. 1).

Calculated sow maternal empty body weight, body protein and body lipid were similar ($P < 0.10$) at farrowing (Table 4). Sow maternal empty body weight loss increased (linear, $P = 0.160$) as soybean meal concentration increased. Sow maternal body lipid loss increased (quadratic, $P = 0.028$), where sows fed 35% soybean meal diets had greater body lipid mobilization compared to sows fed diets with 25 or 30% soybean meal. Maternal body protein loss marginally increased (linear, $P = 0.090$) as dietary soybean meal concentration increased.

There was no evidence for litter count at d 2 or weaning to be different ($P > 0.10$; Table 5), and as a result, no evidence for differences in piglet survivability were observed ($P > 0.10$) across dietary treatments. There was no evidence for difference ($P > 0.10$) in litter weight on d 2, 7, 14, or at weaning, or litter average daily gain, regardless of dietary treatment.

There was no evidence for a difference in lactation length or wean-to-estrus interval ($P > 0.10$) across dietary treatments. Sow serum urea nitrogen concentrations increased (linear, $P < 0.001$) as soybean meal concentration increased; however, there was no evidence for difference ($P > 0.10$) in creatinine concentration.

DISCUSSION

In the present study, linear increases in sow BW, backfat and maternal lipid loss were observed with increasing soybean meal concentration and was most evident with sows fed 35% soybean meal. This is likely a result of decreased lactation feed intake when sows were consuming the 35% soybean meal diet compared to 25 to 30% soybean meal diets. Decreased feed intake has also been observed in Lys titration studies where increasing Lys concentration by increasing soybean meal concentration from 14.5% to 48.5% (Yang et al., 2000a) or from 19 to 34% (Gourley et al., 2017) resulted in decreased sow feed intake. In contrast, Greiner et al. (2018) observed no change in feed intake when soybean meal concentration increased from 24.6 to 34% of the diet, while balancing diets to 1.12% SID Lys. In their study, however, feed intake was limited to a pre-set amount based on parity, which may have limited the ability to find a detectable difference as compared to ad libitum access to feed intake used in our study. Touchette et al. (1998) conducted a Lys titration study during lactation with increasing soybean meal concentration from 18 to 43% and observed no change in feed intake in primiparous sows; however, feed intake was much lower in their study (3.9 to 4.1 kg/d) compared with ours, which also may have limited the ability to find a detectable difference.

It is well documented that when lactation feed intake is inadequate to support litter growth, the sow will mobilize body tissue to compensate in an attempt to maintain litter growth

(Eissen et al., 2003; Yang et al., 2009; Ocepek et al., 2016). Typically, body lipid stores will be mobilized to meet energy deficiency during lactation before protein mobilization (Dourmad et al., 2008). This was validated in the current study with greater maternal body lipid mobilization compared to body protein when voluntary feed intake was reduced, and BW loss occurred.

The differences in feed intake response to increasing soybean meal could be due to an imbalance of amino acids in the diet or anti-nutritional factors in soybean meal. Branched chain amino acids (**BCAA**) Val, Leu and Ile are known to compete for the same AA transporters in the blood-brain barrier as Trp, a precursor for serotonin (Fernstrom, 2005). When BCAA content of the diet increases, brain BCAA concentrations increase, while large neutral AA decrease, resulting in decreased neurotransmitter synthesis (Fernstrom, 2005). Furthermore, BCAA also share the same first step in catabolism, and excess of one BCAA, especially Leu, may expedite the degradation of others, resulting in decreased circulatory levels of Val and Ile (Brosnan and Brosnan, 2006). Total BCAA:Lys increased in the current study from 275 to 314%, as soybean meal concentration increased. Recently, Millet et al. (2015) observed that growing pigs fed increasing levels of Leu had decreased growth and feed intake; however, this was able to be partially recovered by increasing the Val:Leu ratio. Similarly, a Val titration study with weaned pigs observed more severe feed intake reductions when Val:Leu ratios decreased (Meyer et al., 2017).

Data in lactating sows is more limited when evaluating relationships between BCAA. Previously, BCAA ratios had been investigated in lactating sows, and no interactions between BCAA were observed for feed intake or litter performance (Moser et al., 2000). These authors did observe improved litter gain and reduced backfat loss with increased Val, which could also be a function of Val:Leu increasing, with additional Val counteracting the negative impact of high Leu. In the current study, Leu:Lys ratio increased from 130 to 153%, and the Val:Leu ratio decreased from 65 to 55% as the dietary soybean meal concentration increased. Although feed-grade Val was added to the diet to maintain a similar Val:Lys ratio, Val may not have been adequate to counteract increasing Leu. Rather, it may be suggested that diets should also be balanced for Val:Leu to mitigate negative effects on feed intake from increasing Leu as soybean meal or other protein sources (dried distiller's grains with solubles) are increased in lactation diets (Cemin et al., 2019).

Soybeans are known to contain several anti-nutritional factors, a few being trypsin inhibitors, lectin, raffinose and stachyose (Rackis, 1975; Gu et al., 2010). While the heat applied during soybean meal processing typically inactivates the majority of trypsin inhibitors and lectin, raffinose and stachyose maintain their structure through processing (Zdunczyk et al., 2011). Monogastrics lack alpha-galactosidase, the enzyme necessary to break down raffinose and stachyose in the upper intestinal tract, resulting in fermentation in the lower gut. This can cause production of short chain fatty acids and gases, which leads to flatulence, diarrhea and increased catabolism of dietary protein (Zdunczyk et al., 2011). While anti-nutritional factors were not measured in the soybean meal in the current study, it could be hypothesized that the decrease in feed intake in sows consuming diets containing 35% soybean meal may be due to increased concentrations of the anti-nutritional factors mentioned above. Interestingly, we also observed that the variation in ADFI within treatment was greater as the concentration of soybean meal increased. This might indicate that some sows can tolerate higher levels of soybean meal compared to others and this warrants further investigation.

Serum urea nitrogen measures the circulating nitrogen concentration, which is derived from both dietary nitrogen (from metabolism of CP in the diet) and muscle catabolism. The present study observed an increase in serum urea nitrogen concentration with increasing soybean meal and concomitantly dietary CP. (Yang et al., 2000a) fed diets containing increased Lys and CP from soybean meal and also observed an increase in serum urea nitrogen. These authors also speculated that the increase in serum urea nitrogen could be a potential cause for decreased feed intake as they had observed in a previous study (Yang et al., 2000b). To differentiate the cause in increased serum urea nitrogen being derived from dietary CP or endogenous protein catabolism, creatinine was measured in the present study.

Circulating creatinine is used to indicate body protein catabolism. Yang et al. (2009) observed increased creatinine at weaning when sows had been fed 1.0% vs 1.3% total Lys during lactation, suggesting that protein mobilization was increased with the low Lys diet. Touchette et al. (1998) decreased sow body protein mobilization by increasing SID Lys via increasing soybean meal. In the current study, an increase in sow BW, backfat, and maternal BL loss during lactation was observed with increasing soybean meal concentration, which demonstrates the sow is mobilizing body lipid reserves. Thus, the observed increase in serum urea nitrogen with no change in creatinine is reflective of an increase in circulating nitrogen from dietary CP as soybean meal increased without a change in body protein mobilization.

Increasing dietary soybean meal concentration resulted in no effect on growth of suckling pigs even though greater changes in sow BW loss occurred with increasing dietary soybean meal concentration. Similarly, previous studies did not observe a difference in litter growth as soybean meal concentration increased from 19.3 to 34% (Gourley et al., 2017) or 24.6 to 34% (Greiner et al., 2018). This would suggest modern sow genotypes will support high litter growth by mobilizing body reserves, even when feed intake is limited as demonstrated by the sows fed the high soybean meal diet in the current study. Additionally, this would suggest that the amount of

Lys supplied in the current diets was adequate to meet the demand for litter growth with SID Lys intake ranging from 59.9 to 54.6 g/d for 25 to 35% soybean meal diets, respectively.

Despite the changes in BW and maternal BP during lactation, there was no evidence for difference in wean-to-estrus interval. When Lys is undersupplied during lactation, the subsequent reproductive performance can be negatively affected due to increased body protein mobilization (Huang et al., 2013; Gourley et al., 2017). This effect is likely only observed after sows have lost greater than 12% of protein stores during lactation (Clowes et al., 2003). In the present study, sows were projected to only lose 2% maternal BP when fed 35% soybean meal diets. Thus, BP change was not great enough to elicit a negative impact in wean to estrus interval, again suggesting that the range of 54.6 to 59.9 g/d SID Lys was adequate to support subsequent reproductive performance. Additional research is needed to determine if the magnitude of BP and BL loss occurring over multiple lactation periods from consuming high soybean meal concentration diets could lead to negative lifetime reproductive performance.

In summary, increasing soybean meal concentration from 25 to 35% decreased voluntary feed intake in lactating sows, with the greatest magnitude of change occurring as soybean meal was increased from 30 to 35%. Interestingly, there was no evidence for feed intake to be affected in the first 7 days after farrowing. This suggests the decreased feed intake is not a result of the initial transition from a relatively low soybean meal level in the gestation diet compared to the lactation diet. There was no impact on litter growth or wean-to-estrus interval; however, sows fed diets with 35% soybean meal had the greatest farrow-to-wean weight loss and backfat loss, which could impact future reproductive performance or longevity within the herd.

LITERATURE CITED

AOAC International. 1990. Official methods of analysis of AOAC International. 15th ed. AOAC Int., Gaithersburg, MD.

AOAC International. 2006. Official methods of analysis of AOAC International. 15th ed. AOAC Int., Gaithersburg, MD.

Brosnan, J. T., and M. E. Brosnan. 2006. Branched-chain amino acids: enzyme and substrate regulation. J. Nutr. 136:207-211. doi: 10.1093/jn/136.1.207S

Cemin, H. S., M. D. Tokach, S. S. Dritz, J. C. Woodworth, J. M. DeRouchey, and R. D. Goodband. 2019. Meta-regression analysis to predict the influence of branched-chain and large neutral amino acids on growth performance of pigs. J. Anim. Sci. 97:2505-2514. doi: 10.1093/jas/skz118

Clowes, E. J., F. X. Aherne, G. R. Foxcroft, and V. E. Baracos. 2003. Selective protein loss in lactating sows is associated with reduced litter growth and ovarian function. J. Anim. Sci. 81:753-764. doi: 10.2527/2003.813753x

Dourmad, J.-Y., M. Étienne, A. Valancogne, S. Dubois, J. van Milgen, and J. Noblet. 2008. InraPorc: A model and decision support tool for the nutrition of sows. Anim. Feed Sci. Tech. 143:372-386. doi: 10.1016/j.anifeedsci.2007.05.019

Eissen, J. J., E. J. Apeldoorn, E. Kanis, M. W. A. Verstegen, and K. H. d. Greef. 2003. The importance of a high feed intake during lactation of primiparous sows nursing large litters. J. Anim. Sci. 81:594-603. doi: 10.2527/2003.813594x

Fernstrom, J. D. 2005. Branched-chain amino acids and brain function. J. Nutr. 135:1539-1546. doi: 10.1093/jn/135.6.1539S

Gourley, K. M., G. E. Nichols, J. A. Sonderman, Z. T. Spencer, J. C. Woodworth, M. D. Tokach, J. M. DeRouchey, S. S. Dritz, R. D. Goodband, S. J. Kitt, and E. W. Stephenson. 2017. Determining the impact of increasing standardized ileal digestible lysine for primiparous and multiparous sows during lactation. Trans. Anim. Sci. 1:426-436. doi: 10.2527/tas2017.0043

Greiner, L., P. Srichana, J. L. Usry, C. Neill, G. L. Allee, J. Connor, K. J. Touchette, and C. D. Knight. 2018. The use of feed-grade amino acids in lactating sow diets. J. Anim. Sci. Biotechnol. 9:3. doi: 10.1186/s40104-017-0223-z

Gu, C., H. Pan, Z. Sun, and G. Qin. 2010. Effect of soybean variety on anti-nutritional factors content, and growth performance and nutrients metabolism in rat. Int. J. Mol. Sci. 11:1048-1056. doi: 10.3390/ijms11031048

Huang, F. R., H. B. Liu, H. Q. Sun, and J. Peng. 2013. Effects of lysine and protein intake over two consecutive lactations on lactation and subsequent reproductive performance in multiparous sows. Livest. Sci. 157:482-489. doi: 10.1016/j.livsci.2013.07.015

Koketsu, Y., G. D. Dial, J. E. Pettigrew, W. E. Marsh, and V. L. King. 1996. Characterization of feed intake patterns during lactation in commercial swine herds. J. Anim. Sci. 74:1202-1210. doi: 10.2527/1996.74122875x

Meyer, F., C. Jansen van Rensburg, and R. M. Gous. 2017. The response of weaned piglets to dietary valine and leucine. Anim. 11:1279-1286. doi: 10.1017/s1751731116002834

Millet, S., M. Aluwé, B. Ampe, and S. De Campeneere. 2015. Interaction between amino acids on the performances of individually housed piglets. J. Anim.Phys. Anim. Nutr. 99:230-236. doi: 10.1111/jpn.12227

Moser, S. A., M. D. Tokach, S. S. Dritz, R. D. Goodband, J. L. Nelssen, and J. A. Loughmiller. 2000. The effects of branched-chain amino acids on sow and litter performance. J. Anim. Sci. 78:658-667. doi: 10.2527/2000.783658x

NRC. 2012. Nutrient Requirments of Swine. 11th ed. Natl. Acd. Press, Washington, DC.

Ocepek, M., I. Andersen-Ranberg, S. A. Edwards, B. Fredriksen, T. Framstad, and I. L. Andersen. 2016. Can a super sow be a robust sow? Consequences of litter investment in purebred and crossbred sows of different parities. J. Anim. Sci. 94:3550-3560. doi: 10.2527/jas.2016-0386

Rackis, J. J. 1975. Oligosaccharides of Food Legumes: Alpha-Galactosidase Activity and the Flatus Problem, Physiological Effects of Food Carbohydrates. ACS Symposium Series No. 15. American Chemical Society. p. 207-222.

Touchette, K. J., G. L. Allee, M. D. Newcomb, and R. D. Boyd. 1998. The lysine requirement of lactating primiparous sows. J. Anim. Sci. 76:1091-1097. doi: 10.2527/1998.7641091x

Yang, H., J. E. Pettigrew, L. J. Johnston, G. C. Shurson, and R. D. Walker. 2000a. Lactational and subsequent reproductive responses of lactating sows to dietary lysine (protein) concentration. J. Anim. Sci. 78:348-357. doi: 10.2527/2000.782348x

Yang, H. S., J. E. Pettigrew, L. J. Johnston, G. C. Shurson, J. E. Wheaton, M. E. White, Y. Koketsu, A. F. Sower, and J. A. Rathmacher. 2000b. Effects of dietary lysine intake during lactation on blood metabolites, hormones, and reproductive performance in primiparous sows. J. Anim. Sci. 78:1001-1009.

Yang, Y. X., S. Heo, Z. Jin, J. H. Yun, J. Y. Choi, S. Y. Yoon, M. S. Park, B. K. Yang, and B. J. Chae. 2009. Effects of lysine intake during late gestation and lactation on blood metabolites, hormones, milk composition and reproductive performance in primiparous and multiparous sows. Anim. Reprod. Sci. 112:199-214. doi: 10.1016/j.anireprosci.2008.04.031

Zdunczyk, Z., J. Janknowski, J. Juskiewicz, and B. A. Slominski. 2011. Dietary Content and Gastrointestinal Function of Soybean Oligosaccharides in Monogastric Animals. In: T.-B. Ng, editor, Soybean - Biochemistry, Chemistry and Physiology. IntechOpen, Croatia. p. 523-540.

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

	Soybean meal, %		
Ingredient, %	25	30	35
Corn	67.97	63.38	58.84
Soybean meal, 46.5% crude protein	25.00	30.00	35.00
Choice white grease	2.00	2.00	2.00
Limestone	1.28	1.25	1.23
Monocalcium phosphate, 21%	1.80	1.78	1.73
Sodium chloride	0.50	0.50	0.50
L-Lys-HCl	0.34	0.18	0.03
DL-Met	0.09	0.05	0.00
L-Thr	0.17	0.10	0.03
L-Trp	0.03	0.00	0.00
L-Val	0.20	0.12	0.03
Trace mineral premix[2]	0.15	0.15	0.15
Vitamin premix[3]	0.50	0.50	0.50
Total	100	100	100
Calculated analysis			
Standardized ileal digestible amino acids, %			
Lysine	1.05	1.05	1.05
Isoleucine:Lysine	60	68	76
Leucine:Lysine	130	141	153
Methionine:Lysine	32	30	28
Methionine and Cysteine:Lysine	56	56	56
Threonine:Lysine	67	67	67
Tryptophan:Lysine	20	20	23
Valine:Lysine	85	85	85
TBCAA[4]:Lysine	275	295	314
Valine:Leucine	65	60	55
Isoleucine:Leucine	46	48	50
Total Lysine, %	1.18	1.19	1.20
Metabolizable energy, kcal/kg	3,331	3,322	3,316
Net energy, kcal/kg	2,511	2,478	2,447
SID Lysine:NE, g/Mcal	4.25	4.31	4.37
Crude protein, %	18	20	22
Ca, %	0.89	0.89	0.89
P, %	0.74	0.76	0.77
STTD[5] P, %	0.50	0.50	0.50

[1] Sows were fed 2.7 kg per day from d 112 of gestation until farrowing, then *ad libitum* from farrowing until weaning.

[2] Provided per kg of diet: 121 mg Zn from zinc sulfate; 121 mg Fe from iron sulfate; 36 mg Mn from manganese oxide; 18 mg Cu from copper sulfate; 0.3 mg I from calcium iodate; 0.3 mg Se from sodium selenite; 0.12 mg chromium picolinate.

[3] Provided per kg of diet: 8,818 IU vitamin A; 2,204 IU

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vitamin D; 66 IU vitamin E; 4.4 mg vitamin K; 0.04 mg vitamin B12; 83 mg niacin; 28 mg pantothenic acid; 8.3 mg riboflavin; 0.22 mg biotin; 1.65 mg folic acid; 2.2 mg pyridoxine; 551 mg choline; and 50 mg carnitine.

[4] Calculated TBCAA:Lys = Ile:Lys + Leu:Lys + Val:Lys.

[5] STTD= Standardized total tract digestible.

Table 1-2 Chemical analysis of experimental diets (as-fed basis)[1]

	Soybean meal, %		
Item, %	25	30	35
Dry matter	88.6	88.9	89.9
Crude protein	18.3	20.1	22.1
Ca	1.03	1.04	1.08
P	0.71	0.72	0.78

[1] Diet samples were collected from each batch of feed at manufacturing from every fifth bag. Nutrient analysis was conducted in duplicate on composite samples (Ward Laboratories, Kearney, NE). Thus, each sample is a mean of 10 observations.

Table 1-3 Effects of increasing soybean meal concentration fed during lactation on sow performance[1]

	Soybean meal, %				Probability, *P* <	
	25	30	35	SEM	Linear	Quadratic
Number of sows, n	44	43	44	--	--	--
Parity	2.0	2.0	2.0	0.15	0.998	0.157
Sow body weight, kg						
Farrow	219.7	219.0	220.9	4.00	0.619	0.537
Wean	212.5	211.9	209.9	3.84	0.363	0.768
Change (farrow to wean)	-7.3	-7.0	-11.1	1.26	0.017	0.110
Sow backfat, mm						
Farrow	15.9	15.4	16.1	0.51	0.702	0.195
Wean	13.7	13.5	13.3	0.41	0.379	0.985
Change (farrow to wean)	-2.3	-1.9	-2.8	0.31	0.100	0.052
Sow ADFI[2], kg						
d 0 to 7	3.6	3.6	3.6	0.11	0.684	0.798
d 7 to 14	6.5	6.4	6.0	0.13	0.001	0.234
d 14 to wean	7.3	7.1	6.5	0.16	0.001	0.227
Farrow to wean	5.7	5.6	5.2	0.11	0.001	0.314
Lactation length, d	19.5	19.5	19.3	0.14	0.319	0.299
Wean to estrus, d	4.5	4.4	4.4	0.12	0.618	0.891
Serum concentration[3], mg/dL						
Urea nitrogen	20.4	25.4	28.1	1.14	0.001	0.318
Creatinine	3.7	3.6	3.8	0.19	0.580	0.584

[1] A total of 131 sows (Line 241; DNA, Columbus, NE) and their litters were used in a 21-d study.

[2] ADFI = average daily feed intake.

[3] On d 14 of lactation sows were fasted for 10 h then bled. Samples were centrifuged after collection and serum was used in analysis.

Table 1-4 Effects of increasing soybean meal concentration fed during lactation on sow body composition[1]

	Soybean meal, %				Probability, $P <$	
	25	30	35	SEM	Linear	Quadratic
Number of sows, n	44	43	44	--	--	--
Maternal empty body weight[2], kg						
Farrow	210.9	210.2	212.0	3.83	0.619	0.537
Wean	204.0	203.4	201.5	3.66	0.362	0.768
Change, farrow to wean	-6.7	-6.4	-10.7	1.19	0.016	0.110
Maternal body lipid[3], kg						
Farrow	41.3	40.6	41.8	1.19	0.618	0.261
Wean	36.8	36.4	35.7	1.09	0.311	0.817
Change, farrow to wean	-4.47	-3.97	-6.19	0.53	0.016	0.028
Maternal body protein[4], kg						
Farrow	34.5	34.5	34.7	0.66	0.711	0.876
Wean	34.1	34.0	33.7	0.62	0.455	0.785
Change, farrow to wean	-0.45	-0.51	-0.93	0.20	0.090	0.467

[1] A total of 131 sows (Line 241; DNA, Columbus, NE) and their litters were used in a 21-d study.

[2] Maternal EBW (kg) = 0.96 × maternal BW (Eq. 8-49; NRC, 2012).

[3] Maternal BL (kg) = -26.4+ 0.221 × maternal EBW +1.331 × P2 backfat (Eq. 8-50; NRC, 2012).

[4] Maternal BP (kg) = 2.28 + 0.178 × maternal EBW -0.333 × P2 backfat (Eq. 8-51; NRC, 2012).

Table 1-5 Effects of increasing soybean meal concentration fed during lactation on litter performance[1]

	Soybean meal, %				Probability, *P* <	
	25	30	35	SEM	Linear	Quadratic
Number of sows	44	43	44	--	--	--
Litter count, n						
d 2[2]	13.7	13.6	13.6	0.56	0.863	0.988
Wean	13.0	12.9	12.9	0.04	0.963	0.955
Piglet survivability,[3] %	95.2	95.0	95.7	1.00	0.654	0.651
Litter weight, kg						
d 2	20.5	20.2	19.8	0.51	0.297	0.886
d 7[4]	33.0	32.4	33.0	0.35	0.867	0.136
d 14[4]	55.1	54.0	55.5	0.75	0.697	0.128
Wean[4]	70.2	69.2	70.2	1.29	0.995	0.414
Litter ADG, g[4]	3,002	2,937	3,032	72.7	0.724	0.288

[1] A total of 131 sows (Line 241; DNA, Columbus, NE) and their litters were used in a 21-d study.

[2] Cross-fostering occurred irrespective of treatment in an attempt to equalize litter size. Litters were weighed at 48-h, after cross-fostering.

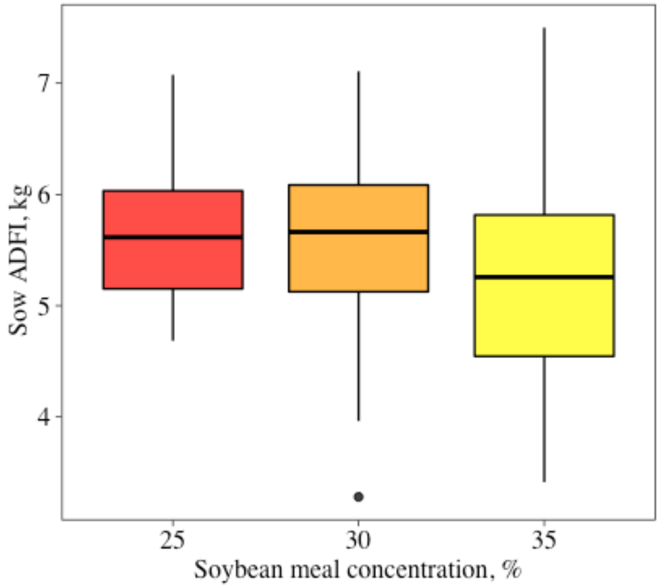
[3] Piglet survivability = litter count at weaning/litter count on d 2.

[4] Litter weight on d 2 was used as a covariate to improve the fit of the model.

SEM = standard error of the mean.

ADG = average daily gain.

Figure 1-1 Box plot of overall sow average daily feed intake by soybean meal level[1]



[1] The horizontal line in each box denotes the treatment median feed intake, while vertical lines indicate variation.

Chapter 2 - Effects of increased lysine and energy feeding duration prior to parturition on sow and litter performance, piglet survival, and colostrum quality

ABSTRACT

A total of 467 sows were used to evaluate the effect of feeding duration of increased lysine (**Lys**) and metabolizable energy (**ME**) prior to farrowing on sow and litter performance, piglet survival, and colostrum quality. Sows were blocked by body weight (**BW**) and parity category on d 106 of gestation, and allotted to 1 of 3 dietary regimens starting on d 107 of gestation: 1) Control: 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 2.7 kg/d lactation feed (28 g SID Lys and 9.4 Mcal ME) until parturition; 2) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition; or 3) 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition. Data were analyzed for treatment within parity effects using the GLIMMIX procedure of SAS. Increasing the duration of feeding additional Lys and ME increased ($P < 0.05$) sow weight gain from d 106 to 113. Sow backfat gain from d 106 to 113 of gestation increased ($P < 0.05$) in gilts and sows fed 3.8 kg/d of the lactation diet starting on d 107 vs. the control regimen. Average total born and born alive piglet birth weight (**BiWt**) was greater ($P < 0.05$) in gilts fed 3.8 kg/d lactation diet starting on d 107 or 113 vs. control, with no evidence ($P > 0.05$) for difference in piglet BiWt in sows or weaning weight in gilts and sows. Piglet mortality after cross-foster to weaning was decreased ($P < 0.05$) in sows fed 3.8 kg/d lactation diet starting on d 113 vs. control or increased lactation diet starting on d 107, but not in gilts. Litter gain from cross-foster to weaning was decreased ($P < 0.05$) in gilts fed 3.8 kg/d lactation diet starting on d 107 compared to control, with no evidence for difference in sows. Colostrum immunoglobulin G was increased ($P < 0.05$) in gilts and sows fed 3.8 kg/d of the lactation diet starting on d 113 compared to control. There was no evidence dietary regimen influenced ($P > 0.05$) piglet colostrum intake or colostrum yield. There was no evidence for difference ($P > 0.05$) among regimens in wean-to-estrus interval, subsequent farrowing rate, or subsequent litter characteristics. In conclusion, feeding increased Lys and ME prior to farrowing increased BW and backfat. Feeding increased Lys and ME when gilts were moved into the farrowing room increased BiWt, but reduced litter growth to weaning, with little evidence sow performance was influenced in this study.

INTRODUCTION

In recent years, a large emphasis has been placed on understanding the requirements of high-producing sows (Tokach et al., 2019). While several studies have been conducted to evaluate changing nutrient requirements in late gestation (d 90 to parturition) and lactation, few studies have focused on the few days immediately before farrowing. This transition period has been defined as the last 10 d of gestation to the first 10 d of lactation (Theil, 2015), with studies involving transition diets starting to be fed between d 104 and 109 of gestation (Loisel et al., 2014; Feyera et al., 2017; Garrison et al., 2017).

Fetal growth rate increases exponentially in late gestation (McPherson et al., 2004), and, in the last 10 d prior to parturition, it is estimated that fetal growth (22.7%), mammary growth (16.8%), and colostrum production (16.1%) represent the majority of the total required standardized ileal digestible (**SID**) lysine (Feyera and Theil, 2017). Additionally, the majority (66%) of the sow metabolizable energy (**ME**) requirement is derived from sow maintenance, resulting in ME and SID Lys requirements increasing by 60 and 149% from d 104 to115 of gestation, respectively (Feyera and Theil, 2017).

Based on a factorial approach, Feyera and Theil (2017) predicted that the ME and SID Lys requirement on the last day of gestation is approximately 13.3 Mcal/d ME and 35 g/d SID Lys, which is a significant increase in energy and Lys required compared to what is typically provided in a corn and soybean meal-based gestation diet. Goncalves et al. (2016a) analyzed the results of multiple trials providing increased feed allowance from d 90 to farrowing and observed an average concentration of 20 g/d of SID Lys supplied to sows, which would be 15 g/d less than the predicted requirement during the final 7 d of gestation (Feyera and Theil, 2017). However, this review (Goncalves et al., 2016a) observed only modest increases if any, in piglet birth weight (**BiWt**). Dourmad et al. (2008) suggested that late gestation ME intake is typically below the level required for maximum nitrogen retention. Therefore, in the last few days before parturition, the sow may be in a negative Lys and energy balance as she partitions exponentially increasing amount of nutrients towards rapid fetal growth (McPherson et al., 2004) and colostrum production (Feyera and Theil, 2017).

Previous trials conducted to evaluate different diet regimens for transition sows have been conducted mostly in small research herds, thus there is a need to confirm these previous findings in larger commercial farms. Thus, the objective of the current experiment was to determine the impact of different feeding durations of increased Lys and energy immediately prior to farrowing on colostrum production, sow and litter performance, and piglet survival under commercial conditions.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This experiment was conducted on a commercial 3,000-sow farm in southern Minnesota during summer 2018 (Christensen Farms, Sleepy Eye, MN). The facilities were environmentally controlled with mechanical ventilation.

A total of 467 mixed parity sows (Fast Large white × PIC Landrace) were used from d 106 of gestation until weaning. On d 106 of gestation, sows were weighed, blocked by body weight (**BW**) within parity category (gilts and sows) and allotted to 1 of 3 dietary treatments. Treatments were fed starting on d 107 of gestation and consisted of: 1) Control: 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) fed until d 113 of gestation, then 2.7 kg/d lactation feed (28 g SID Lys and 9.4 Mcal ME) offered until parturition; 2) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) fed until d 113 of gestation, then 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) offered until parturition; or 3) 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) offered from d 107 of gestation until parturition. Diets were formulated and fed to meet or exceed all other nutrient requirements (NRC, 2012), and were manufactured in Sleepy Eye, MN (Table 1). Sows were hand-fed their respective dietary treatments from d 107 of gestation until parturition, at which point they were fed the lactation diet to approximate *ad libitum* feeding by filling feed hoppers twice daily until weaning. These lactation feeders contained a rod that sows manipulated to dispense feed whenever activated. Feed samples of each diet were collected twice each week from the feeders at the farm. Samples were pooled and used for chemical analysis.

Females were moved from the gestation facility to a farrowing room (approximately d 113 of gestation) weighed and backfat thickness measured. All backfat measurements were performed by the same person, using a Renco Lean Meter (S.E.C. Repro Inc., Quebec, Canada) at the P2 position (last rib, 6 to 8 cm from the midline) on each side of the sow and then taking an average of the two measurements. Each farrowing stall (1.5 m × 2.1 m total, with 0.6 m × 2.1 m for sows) contained a nipple waterer and feeder for the sow, and a rubber mat with a heat lamp for the piglets. Sows were induced (2cc, Lutalyse, Zoetis Inc., Kalamazoo, MI) on the afternoon of d 115 of gestation if parturition had not started. Farrowing surveillance occurred daily from 0300 h to 2400 h. Only litters born during the surveillance period were included to ensure accurate classification of born alive, stillborn, and mummified fetuses. Farrowing assistance was given to sows if presence of a wet pig had not occurred for 45 minutes. For analysis, mummified fetuses (220 total) were excluded from the total born count. Total born was calculated as the sum of born alive and stillborn pigs. Survivability to 24 h was calculated as: [total born - (stillborn + 24 h mortality)]/total born.

During farrowing, the time each piglet was born was recorded, the umbilical cord was cut to 10 cm, the piglet was dried using desiccant and paper towels, identified with an ear tag, and weighed. Stillborn pigs were also weighed and birth time recorded. Within 3 h from the initiation of parturition, a 50 mL sample of colostrum was collected from multiple teats and the number of functional teats was recorded. Colostrum samples were split into two subsamples, 15 mL for colostrum immunoglobin G (**IgG**) analysis, and 35 mL for nutrient analysis (preserved with an 18% Bronopol pellet). Samples were stored at -20°C until analysis.

At 24 h after the birth of the first pig, piglets were individually weighed to calculate colostrum intake. Colostrum intake was calculated using the equation

$$\text{colostrum intake} = -106 + 2.26\ \text{WG} + 200\ \text{BWB} + 0.111\ \text{D} - 1{,}414\ \text{WG/D} \\ + 0.0182\ \text{WG/BWB}$$

The WG represents 24 h piglet weight gain in grams, D is duration of colostrum suckling in minutes, and BWB is body weight at birth in kilograms as described by Theil et al. (2014). Colostrum yield was calculated as the sum of the colostrum intake of the pigs in the litter. If a piglet died before 24 h, the assumption was no colostrum intake by that piglet.

After 24 h, pigs were cross-fostered within treatment to equalize litter size. All piglet mortalities were weighed and the date recorded. Fall-behind piglets, removed due to weight loss or injury between d 3 and d 10 of age, were weighed and moved off test to a nurse sow. At weaning (d 20 ± 3), all piglets were individually weighed to measure piglet and litter gain during lactation. Litter gain was calculated as: litter weaning weight – litter weight after cross foster.

At weaning, sows were weighed, backfat measurements recorded, then moved to gestation stalls and checked twice daily for signs of estrus using a boar and back pressure test. Wean-to-first service interval and d 30 conception rate were collected on 419 of the 423 sows that were weaned. Subsequent litter characteristics were collected on 363 females.

Chemical Analysis

Four samples (1 per week) of gestation diet and 8 samples (1 per week) of lactation diet from within the weekly pooled samples were sent to a commercial laboratory (Ward Laboratories, Kearney, NE) and analyzed in duplicate for crude protein (AOAC 990.03, 2006), calcium (Campbell and Plank, 1991; Kovar, 2003), and phosphorus (Campbell and Plank, 1991; Kovar, 2003).

One colostrum sample (35 mL) per sow was sent to a commercial laboratory (Stearns DHIA Lab, Sauk Centre, MN) and analyzed in duplicate for fat, protein, lactose, and total solids (Combi-Foss milk analyzer, Foss Analytics, Denmark). One colostrum sample (15 mL) per sow was thawed at room temperature, vortexed, diluted to 1:1,000,000, and analyzed in duplicate for

Immunoglobulin G concentration using the Porcine IgG ELISA Quantitation Kit (Bethyl Laboratories, Montgomery, TX).

Statistical Analysis

Data were analyzed using generalized linear mixed model where dietary regimen within parity category (gilt or sow) was a fixed effect and block was a random effect. Statistical models were fit using the GLIMMIX procedure of SAS (Version 9.4, SAS Institute, Inc., Cary, NC). During lactation, 44 sows were removed from the study due to becoming a nurse sow (n=24), poor health (n=11), or poor milking ability (n=9). These sows were not included in analysis for litter performance after 24 h.

Sow body weight, backfat depth, litter weights, mean piglet body weights, litter gains, colostrum quality (fat, protein, lactose, and solids), colostrum yield, and colostrum intake were fit using a normal distribution. Total born, litter counts, and wean-to-estrus interval were fit using a negative binomial distribution. Percentage born alive, stillborn, fall-behind pigs, survivability, mortality, estrus by d 7, and subsequent farrowing rate were fit using a binomial distribution. Colostrum IgG concentration was analyzed using a log transformation.

Covariates were used if they significantly improved the model fit and were biologically consistent. Residuals and the Bayesian Information Criterion were used as an indication of improved model fit. Total born was used as a covariate for total born litter weight and mean (**BiWt**). Born alive was used as a covariate for born alive and 24 h litter weights, and mean piglet born alive birth and 24 h weights. Pig-to-teat ratio was used as a covariate for 24 h litter gain, colostrum yield and intake. Litter size after cross foster was used as a covariate for litter weight and piglet weight after cross foster and at weaning.

RESULTS AND DISCUSSION

Sow BW change

There was no evidence of difference (*P* > 0.05; Table 2) in sow BW and backfat depth at allotment and gestation length across regimens within parity category which validates the allotment to treatment. At the time sows and gilts were moved to the farrowing room (d 113 ± 2), a regimen within parity category effect was observed where gilts fed 3.8 kg/d lactation diet starting on d 107 were 6.1 kg heavier (*P* < 0.05) than control gilts, with gilts that received 3.8 kg/d lactation diet starting on d 113 intermediate. Sows fed 3.8 kg/d lactation diet starting on d 107 were heavier (*P* < 0.05) than sows fed control or those that received 3.8 kg/d lactation diet starting on d 113. As a result, a main effect of feeding regimen was observed for sow weight change from allotment to movement to the farrowing rooms where gilts and sows fed 3.8 kg/d lactation diet starting on d 107 gained more weight (*P* < 0.05) than females that received 3.8 kg/d lactation diet starting on d 113, and females fed either regimen gained more weight than control-fed gilts or sows. This was expected due to the increased SID Lys and energy provided to females beginning at d 107 or d 113 compared to the control feeding regimen. Previous studies that have evaluated increased feeding strategies starting on d 90 of gestation suggested that an additional 16.6 g/d SID Lys and 9.6 Mcal/d ME resulted in an additional 6.9 kg of BW gain (Goncalves et al., 2016a). While the dietary regimens in the current study would have been fed for a shorter duration, the much higher concentration of SID Lys (40 g/d) and ME intake (13.3 Mcal/d) resulted in similar BW gain as those where feed intake was increased from d 90 of gestation to farrowing (Yang et al., 2009; Mallmann et al., 2018).

There was no evidence for difference (*P* > 0.05) in sow body weight at weaning or sow weight loss from movement to the farrowing rooms to weaning, regardless of dietary regimen.

However, there was numerically greater body weight loss during lactation in females that received 3.8 kg/d lactation diet starting on d 107 compared to control-fed females. Additionally, there was no evidence for difference ($P > 0.05$) in female body weight change from allotment to weaning, indicating that the additional weight gain observed peripartum was subsequently lost during the lactation period. The body weight loss observed could be due in part to reduced feed intake by females that were supplied 3.8 kg/d lactation diet starting on d 107; however, individual lactation feed intake was not collected in our study to confirm. Previous studies have shown that increased sow feed allowance in late gestation increases backfat gain prior to parturition which consequently leads to decreased feed intake and increased body weight loss during the lactation period (Weldon et al., 1994; Koketsu et al., 1996; Mallmann et al., 2018)

Sow backfat

Backfat thickness at the time of movement into the farrowing house was increased ($P < 0.05$) in gilts that received lactation diet starting on d 107 compared to those starting on d 113, with control gilts intermediate. There was no evidence for difference in backfat thickness in sows at time of movement from gestation to the farrowing room. A main effect of feeding regimen on backfat change from allotment to movement from gestation to the farrowing room was observed where females that received 3.8 kg/d lactation diet starting on d 107 had increased ($P < 0.05$) backfat gain compared to control females, but this change was small (0.5 mm). Similarly, increased backfat was observed when SID Lys (Yang et al., 2009) or gestation feed amount (Mallmann et al., 2019) was increased from d 90 to 112 in females. The NRC (2012) suggests that if ME for body maintenance, fetal growth and maternal body protein are not met, sows will mobilize body lipid stores. The present study demonstrates that 1) the ME requirement for maintenance and fetal growth was met by feeding the control regimen because backfat change was positive from d 106 to movement to farrowing room; 2) the increased nutrient supply that resulted in increased body weight was partially allocated towards sow body fat, regardless of parity.

There was no evidence for difference (*P* > 0.05) in backfat loss from the time of sow entry into the farrowing rooms until weaning. As a result, a main effect of regimen was observed for sow backfat thickness at weaning, where gilts and sows that received lactation diet starting on d 107 had increased (*P* < 0.05) backfat compared to the control or those that received 3.8 kg/d lactation diet starting on d 113. This agrees with previous studies, where increasing prepartum feed up to 3.3 kg/d (21 g SID Lys and 19.8 Mcal ME) from d 90 to farrowing in gilts resulted in increased backfat at d 112 of gestation and at weaning compared to females restricted to 1.7 kg/d gestation feed (Mallmann et al., 2019). Similarly, Cools et al. (2014) observed decreased backfat mobilization from d 104 to weaning when sows consumed feed ad libitum compared to restricted intake pre-farrowing. These results demonstrate that the additional backfat gained peripartum from increased feed intake prior to farrowing did not result in increased backfat loss during lactation. Rather additional feed in the peripartum period resulted in increased backfat thickness at weaning compared females restricted fed in the peripartum.

Litter weight, average piglet weight and litter gain

There was a regimen within parity effect for total born litter weight, born alive litter weight, and 24 h litter weight, where gilts fed 3.8 kg/d lactation diet starting on d 113 or d 107 had heavier (*P* < 0.05; Table 3) litters compared to control gilts. Sows that received 3.8 kg/d lactation diet starting on d 107 had heavier (*P* < 0.05) total born and born alive litters at birth compared to sows fed 3.8 kg/d lactation diet starting on d 113, and control sows were intermediate.

A regimen within parity effect was observed for mean piglet body weight for total born and born alive piglets, where gilts fed 3.8 kg/d lactation diet starting on d 107 or 113 had heavier ($P < 0.05$) piglets compared to control gilts, with no regimen difference for average piglet birth weight in piglets from sow litters. The literature regarding additional Lys and energy fed to gilts varies in the degree of response. Amdi et al. (2014) observed heavier piglet birth weights from fat gilts (19 mm) compared to thin gilts (14 mm) which had been restricted to a lower Lys and energy diet during gestation. Yang et al (2009) observed increased piglet BiWt (100 g) from gilts fed increased total Lys (0.6 vs 0.8%) starting on d 80 of gestation. Whereas Goncalves et al. (2016b) observed a modest increase (28 g) in piglet BiWt from gilts fed 20 g SID Lys and 6.5 Mcal net energy (**NE**) from d 90 of gestation, compared to gilts fed 4.5 Mcal NE. In the current study, the much higher level of amino acids (**AA**) and energy (40 g/d SID Lys and 13.3 Mcal ME) combined may have allowed additional fetal growth to occur beyond what previous studies have observed. In fact, the additional ME intake may have allowed for gilts to be closer to the energy level required for maximum nitrogen retention in conceptus and maternal tissues (Dourmad et al., 2008).

There was no evidence ($P > 0.05$) for difference in average piglet BiWt in sow litters. Similar to the literature, increasing Lys and energy resulted in little or no improvement in piglet BiWt from multiparous sows (Goncalves et al., 2016b; Wiegert et al., 2019; Mallmann et al., 2018). In a review, Goncalves et al. (2016a) summarized that a 1 kg/d increased feed allowance from d 90 of gestation modestly (+30 g) increased piglet BiWt. These results demonstrate that control regimen dietary intake of Lys and energy prior to farrowing were adequate for fetal growth in sows given the level of productivity. The difference in piglet BiWt response of regimen between gilts and sows may be due to the extra SID Lys and energy above normal estimated requirements satisfying gilt maternal protein deposition, maintenance, and fetal growth. Older parity sows (P4+) have a flatter slope for maternal protein deposition (NRC, 2012) and additional energy consumed does not appear to be partitioned towards fetal growth despite an increase in sow body weight. Additionally, the body condition of sows when moved (d 113) to the farrowing room (18 mm) suggests that our sows may not have been at a body condition to respond to increased Lys and energy.

Born alive BiWt CV was lower ($P < 0.05$) in gilts fed 3.8 kg/d lactation diet starting on d 113 compared to those fed the control regimen. This demonstrates less variation in BiWt in gilts that were fed additional SID Lys and energy for 3 d prior to farrowing. However, Mallmann et al. (2019) observed no evidence for difference in gilt litter BiWt CV when fed 21 g SID Lys and 10.8 Mcal ME for 30 d during late gestation. This difference may be due to the current study feeding almost twice the SID Lys (40 g/d) for a shorter period than Mallmann, et al. (2019), allowing a reduction in BiWt CV to be observed. Furthermore, in sows, there was no evidence for difference ($P > 0.05$) in BiWt CV in piglets, which is in agreement with previous literature (Craig et al., 2017).

Piglets were cross-fostered up to 48 h within dietary regimens to equalize litter size (Table 4). Litter weight, litter count, and average pig body weight after cross-fostering was similar ($P > 0.05$) across dietary regimens. There was no evidence for difference ($P > 0.05$) in litter weight, individual piglet body weight, or litter count at weaning regardless of dietary regimen. However, litter gain from 48 h to weaning was decreased ($P < 0.05$) in gilts that received 3.8 kg/d lactation diet starting on d 107 compared to the control fed gilts, with no evidence for difference in sows. This was an unexpected result because earlier observational studies (Bergstrom, 2011; Douglas et. al., 2013) suggested that an increase in piglet BiWt also results in an increase in piglet weaning weight. One potential explanation for the reduction in litter gain in the current study is that increased weight gain of sows prior to farrowing may have had a negative effect on lactation feed intake, which resulted in less milk production and consequently reduced piglet growth. It is documented that reduced or restricted feed intake during lactation results in reduced litter gain and weaning weights compared to a high lactation feed intake (Craig et al., 2017). Several studies have observed that increased body weight and backfat gain prior to parturition resulted in decreased voluntary feed intake during lactation (Weldon et al., 1994; Mallmann et al., 2018) which could lead to reduced milk output. If the sow is not able to mobilize enough body tissue to balance the reduced energy or AA from feed intake, milk production will be reduced leading to reduced litter growth. Cools et al. (2014) demonstrated that fat sows (> 22 mm back fat at d 108) had reduced litter weaning weights when fed ad libitum peripartum compared to thin sows (<18 mm), and concluded that additional feed intake from d 108 of gestation through parturition tended to have a positive effect on litter weaning weights as long as the sows were not over conditioned peripartum. In the current study, backfat averaged 21.3 mm when moved to farrowing (d 113) for the gilts that received 3.8 kg/d starting on d 107 of gestation. This would classify approximately 50% of females on that feeding regimen in the fat category of the Cools et al. (2014) study, thus potentially explaining why the additional feed prior to farrowing was not a benefit to weaning weights in contrast to the benefit observed in BiWt.

Litter characteristics

There was no evidence for difference (*P* > 0.05) in total born, born alive, stillborn, and litter size at 24 h, or survival of piglets to 24 h regardless of dietary regimen. Several studies report an increase in stillborn rate when sows (Goncalves et al., 2016b) or gilts (Mallmann et al.,

2019) are supplied with an increased feed allowance from d 90 of gestation to farrowing. Conversely, no difference in stillborn rate has been observed in gilts (Goncalves et al, 2016b), or multiparous sows (Mallmann et al., 2018; Che et al., 2019; Wiegert, 2019). This discrepancy in stillborn data may be due to the variation in sample size or assistance protocol during farrowing, thus making it difficult to conclude an effect on stillborn rate in the literature.

Wean age was similar across all dietary regimens and averaged 20.7 d. There was no evidence for difference in the percentage of pigs recorded as fallbacks, regardless of regimen. Mortality after cross-fostering to weaning was lower ($P < 0.05$) in sows that received 3.8 kg/d lactation diet starting on d 113 compared to control sows, with no evidence for difference in gilts. This resulted in a greater ($P < 0.05$) percentage of pigs weaned from sows that received 3.8 kg/d of lactation diet starting on d 113 compared the control sows or sows that received lactation diet starting on d 107, again with no change in gilts fed different regimens. Although only numerically different, after cross-fostering the 3.8 kg/d lactation diet starting on d 113 regimen had 0.5 less pigs per litter than the other two regimens which could have allowed for less competition, leading to fewer mortalities. There are few studies that evaluate pre-weaning mortality when late gestation feeding treatments were applied, and they typically have small sample sizes per treatment (10 to 30 sows). Regardless, no evidence for differences in pre-weaning mortality was observed in gilts (Mallmann, et al., 2019) or sows (Che et al., 2019) fed 21 g/d SID Lys from d 90 of gestation, or multiparous sows fed 1.5 to 4.5 kg/d lactation diet on d 104 of gestation (Garrison et al., 2017).

Colostrum composition and yield

Colostrum fat and total solids were decreased ($P < 0.05$) in sows that received the lactation diet starting on d 107 compared to the control sows, with no evidence for difference observed in gilts (Table 5). Of the colostrum components, fat is the easiest to change through nutritional strategies (Farmer and Quesnel, 2009). Typically, the addition of fat in the diet prior to parturition will increase fat content in colostrum (Krogh et al., 2012) or fatty acid profile (Decaluwe et al., 2014). Recently, no evidence for difference was reported in sows fed increased energy on d 90 (Che et al, 2019) or energy and Lys on d 80 of gestation (Yang et al, 2009). However it has been demonstrated that restricting feed intake prior to parturition (1.0 vs 3.7 kg/d) increased colostrum fat content (Goransson, 1990). Whereas over feeding in late gestation can harm mammogenesis by depositing excess fat in the mammary tissues (Farmer and Sorensen, 2001). Therefore, the decrease in colostrum fat in the current study could be due to over conditioning sows with the increased Lys and energy for 3 to 8 d prior to farrowing, resulting in excess fat in the mammary tissue.

There was no evidence for difference ($P > 0.05$) in colostrum protein or lactose concentrations due to dietary regimens. Previous literature is inconsistent on colostrum composition changes due to increasing energy and Lys by feed amount or ingredient composition prior to farrowing. Increasing gestation feed amount from 1.5 to 4.5 kg/d for 7 d prior to farrowing increased colostrum lactose and decreased protein (Decaluwe et al., 2014). In a late gestation energy and AA study, no change in lactose, protein, or total solids in colostrum occurred (Che et al., 2019). Large changes in colostrum composition occur within the first 24 h after birth of first pig, and also differ between anterior and posterior teats (Hurley, 2015). Therefore, differences in time or method of sample collection may have led to the inconsistent response in the literature.

Immunoglobulin G, which provides passive immunity to the piglet (Rooke and Bland, 2002), was increased ($P < 0.05$) in both gilts and sows that received 3.8 kg/d lactation diet starting on d 113 compared to the control, which was largely driven by the increase in the gilts. Increasing AA in late gestation (Che et al., 2019) or feed allowance (Decaluwe et al., 2014) did not result in increased IgG concentrations. Interestingly, Decaluwe et al. (2014) observed a numerical reduction (153 vs. 249 g) in IgG concentration in fat (<23 mm backfat) compared to thin sows. As previously mentioned, sows in the current study were heavy conditioned in late gestation, and the additional energy resulted in increased backfat gain and may have decreased the IgG concentration in the colostrum of those fed 3.8 kg/d lactation diet starting on d 107.

In the current study, sow colostrum yield and piglet colostrum intake had no evidence for difference ($P > 0.05$) due to dietary regimen applied pre-farrow. Previous research observed that moderate conditioned (17 to 22 mm backfat) sows consuming ad libitum feed prior to parturition expressed greater colostrum yield compared to those restricted to 1.5 kg/d which mobilized body reserves prior to farrowing (Decaluwe et al., 2014). Wiegert et al. (2019) observed an increase in colostrum yield when sows were provided 3.0 or 4.5 kg/d lactation diet compared to 1.5 kg/d beginning on d 104 of gestation, but caution must be used in interpretation as only 10 sows were used per treatment in their study. Conversely, Mallmann et al. (2019) observed a linear decrease in colostrum yield as gestation feed amount increased from 1.8 to 3.3 kg/d starting at d 90 of gestation. However, this is likely due to the difference in backfat change from d 90 to parturition, where fat sows (>22 mm of backfat) are known to have decreased colostrum yield (Decaluwe et al., 2014). We speculate that the females in the current study fed the control diet were not restricted the nutrients needed to synthesize colostrum, as backfat prior to farrowing was not mobilized to support colosotrogenesis (Farmer and Quesnel, 2009). Therefore, the reason colostrum yield did not change when sows were supplied with additional feed prior to farrowing could be due to requirements for colostrogenesis being met and additional Lys and energy not being partitioned towards colostrum, or that the range in sow body condition was not changed at a great enough magnitude (0.2 to 0.9 mm gain in backfat) 7 d prior to parturition to allow for an observed change in colostrum yield due to consuming increased energy and Lys.

Reproductive performance

There was no evidence for difference (*P* > 0.05) in wean-to-estrus interval, percentage of females in estrus by d 7, or farrowing rate regardless of dietary regimen that had been fed in the previous transition period (Table 6). In addition, total born or percentage born alive, stillborn, or mummified in the subsequent litter were similar (*P* > 0.05) across dietary regimens that had been fed in the previous transition period. Several other studies have also noted no evidence for differences in wean-to-estrus interval or females in estrus by d 7, total born or born alive due to late gestation feeding levels in the previous parity (Goncalves et al., 2016b; Garrison et al., 2017; Mallman et al., 2018; 2019). This suggests that the changes in body weight and backfat loss during lactation in the current study were not severe enough to effect follicular development (Clowes et al., 2003) or embryonic survival (Vinsky et al., 2006), thus leading to no evidence for differences in subsequent reproductive performance.

In summary, feeding increased Lys and energy starting on d 107 or 113 of gestation increased weight gain and backfat depth of gilts and sows peripartum compared to the control regimen. There was no evidence the additional weight and backfat gain pre-farrowing resulted in weight or backfat loss during the lactation period. Average piglet body weight for total born and born alive pigs was increased in gilts fed increased Lys and energy starting on d 107 or 113 of gestation. However, litter gain to weaning was reduced in gilts fed increased Lys and energy starting at d 107 of gestation compared to the control gilts resulting in no change in weaning weights. There was reduced piglet mortality from sows fed increased Lys and energy starting on d 113 of gestation compared to sows fed the control regimen. Colostrum yield and intake, and subsequent reproductive performance were unaffected by dietary regimens. It can be concluded that with this level of herd productivity and above average sow body condition, feeding increased Lys and energy to gilts at the time of movement to farrowing rooms (approximately d 113 of gestation) may be adequate to meet the additional Lys and energy requirements for fetal growth, as measured by increased piglet BiWt in gilts. There was little evidence that feeding increased Lys and energy prior to farrowing impacted sow performance.

LITERATURE CITED

AOAC International. 2006. Official methods of analysis of AOAC International. 15th ed. AOAC Int., Gaithersburg, MD.

Amdi, C., L. Giblin, T. Ryan, N. C. Stickland, and P. G. Lawlor. 2014. Maternal backfat depth in gestating sows has a greater influence on offspring growth and carcass lean yield than maternal feed allocation during gestation. Animal. 8:236-244. doi: 10.1017/S1751731113002073

Bergstrom, J. R. 2011. Effects of birth weight, finishing feeder design, and dietary astaxanthin and ractopamine HCl on the growth, carcass, and pork quality characteristics of pigs; and meta-analyses to improve the prediction of pork fat quality. PhD. Diss., Kansas State University, Manhattan, KS.

Campbell, C. R. and C. O. Plank. 1991. Sample Preparation. In: C. O. Plank, editor, Plant analysis reference procedures for the southern region of the United States. Southern Cooperative Series Bulletin #368. p. 1-11.

Che, L., L. Hu, C. Wu, Q. Xu, Q. Zhou, X. Peng, Z. Fang, Y. Lin, S. Xu, B. Feng, J. Li, J. Tang, R. Zhang, H. Li, P. K. Theil, and Wu. 2019. Effects of increased energy and amino acid intake in late gestation on reproductive performance, milk composition, metabolic, and redox status of sows1. J. Anim. Sci. 97:2914-2926. doi: 10.1093/jas/skz149

Clowes, E. J., F. X. Aherne, G. R. Foxcroft, and V. E. Baracos. 2003. Selective protein loss in lactating sows is associated with reduced litter growth and ovarian function. J. Anim. Sci. 81:753-764. doi: 10.2527/2003.813753x

Cools, A., D. Maes, R. Decaluwe, J. Buyse, T. A. van Kempen, A. Liesegang, and G. P. Janssens. 2014. Ad libitum feeding during the peripartal period affects body condition, reproduction results and metabolism of sows. Anim. Reprod. Sci. 145:130-140. doi: 10.1016/j.anireprosci.2014.01.008

Craig, A., A. Gordon, and E. Magowan. 2017. Understanding the drivers of improved pig weaning weight by investigation of colostrum intake, sow lactation feed intake, or lactation diet specification. J. Anim. Sci. 95:4499-4509. doi: 10.2527/jas2017.1790

Decaluwe, R., D. Maes, A. Cools, B. Wuyts, S. De Smet, B. Marescau, P. P. De Deyn, and G. P. Janssens. 2014. Effect of peripartal feeding strategy on colostrum yield and composition in sows. J. Anim. Sci. doi: 10.2527/jas2014-7612

Dourmad, J.-Y., M. Étienne, A. Valancogne, S. Dubois, J. van Milgen, and J. Noblet. 2008. InraPorc: A model and decision support tool for the nutrition of sows. Anim. Feed Sci. Tech. 143:372-386. doi: 10.1016/j.anifeedsci.2007.05.019

Douglas, S. L., S. A. Edwards, E. Sutcliffe, P. W. Knap, and I. Kyriazakis. 2013. Identification of risk factors associated with poor lifetime growth performance in pigs. J. Anim. Sci. 91:4123-4132. doi: 10.2527/jas.2012-5915

Farmer, C., and H. Quesnel. 2009. Nutritional, hormonal, and environmental effects on colostrum in sows. J. Anim. Sci. 87 (Suppl 13):56-64. doi: 10.2527/jas.2008-1203

Farmer, C., and M. T. Sorensen. 2001. Factors affecting mammary development in gilts. Livest. Prod. Sci. 70:141-148. doi: 10.1016/S0301-6226(01)00207-X

Feyera, T., C. K. Hojgaard, J. Vinther, T. S. Bruun, and P. K. Theil. 2017. Dietary supplement rich in fiber fed to late gestating sows during transition reduces rate of stillborn piglets. J. Anim. Sci. 95:5430-5438. doi: 10.2527/jas2017.2110

Feyera, T., and P. K. Theil. 2017. Energy and lysine requirements and balances of sows during transition and lactation: A factorial approach. Livest. Sci. 201:50-57. doi: 10.1016/j.livsci.2017.05.001.

Garrison, C., E. van Heughten, J. G. Wiegert, and M. Knauer. 2017. Got Colostrum? Effect of diet and feeding level on piglet colostrum intake and piglet quality. J. Anim. Sci. 95:113-113. doi: 10:2527/asasmw.2017.12.236.

Goncalves, M. A. D., S. S. Dritz, M. D. Tokach, J. H. Piva, J. M. DeRouchey, J. C. Woodworth, and R. D. Goodband. 2016a. Fact sheet increased late gestation feed intake. J. Swine Health Prod. 24:264-266.

Goncalves, M. A. D., K. M. Gourley, S. S. Dritz, M. D. Tokach, N. M. Bello, J. M. DeRouchey, J. C. Woodworth, and R. D. Goodband. 2016b. Effects of amino acids and energy intake during late gestation of high-performing gilts and sows on litter and reproductive performance under commercial conditions. J. Anim. Sci. 94:1993-2003. doi: 10.2527/jas.2015-0087

Goransson, L. 1990. The effect of late pregnancy feed allowance on the milk composition of the sow's colostrum and milk. Acta. Vet. Scand. 31:109-115.

Hurley, W. L. 2015. Composition of sow colostrum and milk. In: C. Farmer, editor, The gestating and lactating sows. Wageningen Academic Publishers, Wageningen, The Netherlands. p. 193-229.

Koketsu, Y., G. D. Dial, J. E. Pettigrew, W. E. Marsh, and V. L. King. 1996. Characterization of feed intake patterns during lactation in commercial swine herds. J. Anim. Sci. 74:1202-1210. doi: 10.2527/1996.74122875x

Kovar, J. L. 2003. Method 6.3 Inductively coupled plasma spectroscopy. In: J. Peters, editor, Recommended methods of mature analysis publication A3769. Univ. of Wisconsin Extension, Madison, WI. p. 41-43.

Krogh, U., C. Flummer, S. K. Jensen, and P. K. Theil. 2012. Colostrum and milk production of sows is affected by dietary conjugated linoleic acid. J. Anim. Sci. 90:366-368. doi: 10.2527/jas53834

Loisel, F., C. Farmer, P. Ramaekers, and H. Quesnel. 2014. Colostrum yield and piglet growth during lactation are related to gilt metabolic and hepatic status prepartum. J. Anim. Sci. 92:2931-2941. doi: 10.2527/jas2013-7472

Mallmann, A. L., F. B. Betiolo, E. Camilloti, A. P. G. Mellagi, R. R. Ulguim, I. Wentz, M. L. Bernardi, M. A. D. Goncalves, R. Kummer, and F. P. Bortolozzo. 2018. Two different feeding levels during late gestation in gilts and sows under commercial conditions: impact on piglet birth weight and female reproductive performance. J. Anim. Sci. 96:4209-4219. doi: 10.1093/jas/sky297

Mallmann, A. L., E. Camilotti, D. P. Fagundes, C. E. Vier, A. P. G. Mellagi, R. R. Ulguim, M. L. Bernardi, U. A. D. Orlando, M. A. D. Goncalves, R. Kummer, and F. P. Bortolozzo. 2019. Impact of feed intake during late gestation on piglet birth weight and reproductive performance: a dose-response study performed in gilts. J. Anim. Sci. 97:1262-1272. doi: 10.1093/jas/skz017

McPherson, R. L., F. Ji, G. Wu, J. R. Blanton, and S. W. Kim. 2004. Growth and compositional changes of fetal tissues in pigs. J. Anim. Sci. 82:2534-2540. doi: 10.2527/2004.8292534x

NRC. 2012. Nutrient Requirments of Swine. 11th ed. Natl. Acd. Press, Washington, DC.

Rooke, J. A., and I. M. Bland. 2002. The acquisition of passive immunity in the new-born piglet. Livest. Prod. Sci. 78:13-23. doi: 10.1016/S0301-6226(02)00182-3

Theil, P. K., C. Flummer, W. L. Hurley, N. B. Kristensen, R. L. Labouriau, and M. T. Sorensen. 2014. Mechanistic model to predict colostrum intake based on deuterium oxide dilution technique data and impact of gestation and prefarrowing diets on piglet intake and sow yield of colostrum. J. Anim. Sci. 92:5507-5519. doi: 10.2527/jas2014-7841

Theil, P. K. 2015. Transition feeding of sows. In: C. Farmer, editor, The gestating and lactating sow. Wageningen Academic Publishers. The Netherlands. P. 147-167.

Tokach, M. D., M. B. Menegat, K. M. Gourley, and R. D. Goodband. 2019. Review: Nutrient requirements of the modern high-producing lactating sow, with an emphasis on amino acid requirements. Animal. 13:2967-2977. doi: 10.1017/S1751731119001253

Vinsky, M. D., S. Novak, W. T. Dixon, M. K. Dyck, and G. R. Foxcroft. 2006. Nutritional restriction in lactating primiparous sows selectively affects female embryo survival and overall litter development. Repro. Fert. Dev. 18:347-355.

Wiegert, J. G. 2019. Effects of practically increasing amino acids and energy in late gestation on colostrum intake, colostrum composition and sow performance. PhD Diss. North Carolina State University.

Weldon, W. C., A. J. Lewis, G. F. Louis, J. L. Kovar, M. A. Giesemann, and P. S. Miller. 1994. Postpartum feeding hypophagia in primiparous sows: I. Effects of gestation level on feed intake, feeding behavior, and plasma metabolite concentrations during lactation. J. Anim. Sci. 72:387-394. doi: 10.2527/1994.722387x

Yang, Y. X., S. Heo, Z. Jin, J. H. Yun, J. Y. Choi, S. Y. Yoon, M. S. Park, B. K. Yang, and B. J. Chae. 2009. Effects of lysine intake during late gestation and lactation on blood metabolites, hormones, milk composition and reproductive performance in primiparous and multiparous sows. Anim. Reprod. Sci. 112:199-214. doi: 10.1016/j.anireprosci.2008.04.031

Table 2-1 Diet composition (as-fed)[1]

Item	Gestation	Lactation
Ingredient, %		
Corn	45.29	48.12
Soybean meal	4.52	25.14
DDGS[2]	12.20	5.00
Bakery meal	10.00	15.00
Soybean hulls	12.20	--
Corn oil	1.23	2.90
Dicalcium phosphate, 18.5% P	1.88	1.86
Limestone	0.66	0.61
Lysine-HCl	0.26	0.34
Salt	0.27	0.23
L-Threonine	0.06	0.12
DL-Methionine	0.02	0.06
Vitamin and mineral premix[3]	0.16	0.16
Choline chloride, 70%	0.13	0.13
SalCurb[4]	0.33	0.33
Total	100	100
Calculated analysis		
Standardized ileal digestible (SID) amino acids, %		
Lysine	0.62	1.06
Methionine:lysine	36	29
Methionine and cysteine:lysine	54	54
Threonine:lysine	64	64
Tryptophan:lysine	18	18
Valine:lysine	70	70
Isoleucine:lysine	63	63
Total lysine, %	0.77	1.21
Crude protein, %	14.0	18.3
Metabolizable energy, kcal/kg	3,212	3,593
Net energy, kcal/kg	2,300	2,520
Calcium, %	0.85	0.85
Phosphorus, %	0.74	0.72
Chemical analysis[5]		
Dry matter	89.1	88.9
Crude protein	14.9	19.0
Calcium	0.90	0.92
Phosphorus	0.73	0.71

[1] Diets were fed according to regimen as follows: 1) 2.0 kg/d gestation feed until d 113 of gestation, then 2.7 kg/d lactation feed until parturition; 2) 2.0 kg/d gestation feed until d 113 of gestation, then 3.8 kg/d lactation feed until parturition; and 3) 3.8 kg/d lactation feed from d 107 of gestation until parturition.

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[2] Dried distillers' grain with solubles.

[3] Provided per kg complete feed: 10,000 IU vitamin A; 500 IU vitamin D3; 50 µg 25(OH)D_3 (Hy-D; DSM); 100 IU vitamin E; 0.04 mg vitamin B12; 10 mg vitamin B2; 45 mg niacin; 35 mg d-pantothenic acid; 4.5 mg menadione; 1.35 mg folic acid, 2.2 mg thiamine; 3.3 mg pyridoxine; 0.22 mg biotin; 0.30 mg selenium; 20 mg Cu from copper chloride; 100 mg Fe from iron sulfate; 130 mg Zn from zinc sulfate; 50 mg Mg from Mg oxide; 1.13 mg I from I sulfate.

[4] Kemin Industries Inc. (Des Moines, IA).

[5] Diet samples were collected twice weekly from the feeders (4 or 8 weeks for gestation and lactation, respectively). Nutrient analysis was conducted in duplicate on the weekly pooled samples (Ward Laboratories, Kearney, NE).

Table 2-2 Increased lysine and energy feeding duration prior to parturition on sow performance within parity catergory[1]

	Gilts				Sows			
Response	Control	d 113	d 107	SEM	Control	d 113	d 107	SEM
Farrowing count, n	45	46	45	--	111	108	112	--
Gestation length, d	115.7	115.7	115.8	0.12	115.7	115.8	115.8	0.08
Sow BW, kg								
d 106	224.4	224.2	224.9	3.37	276.7	276.2	276.2	2.19
Loading[2,3]	226.9^{b}	227.9^{ab}	233.0^{a}	3.37	279.8^{b}	279.7^{b}	284.9^{a}	2.20
Post-farrow[4]	203.1	203.9	209.2	2.96	251.7	252.5	256.6	1.92
Weaning	182.0	181.8	184.8	3.89	231.3	232.9	235.9	2.65
Sow weight change, kg								
d 106 to loading[5]	2.1	4.0	7.1	0.87	2.4	3.4	8.8	0.56
Loading[2] to weaning	-44.1	-46.5	-49.5	2.68	-47.5	-46.4	-49.5	1.84
Post farrow-weaning	-20.4	-22.5	-25.5	2.64	-19.5	-19.5	-20.7	1.80
d 106 to weaning	-41.9	-42.5	-42.0	2.8	-44.9	-43.0	-40.3	1.91
Sow backfat, mm								
d 106	20.0	19.0	20.4	0.55	18.1	18.0	17.7	0.35
Loading[2,3]	20.5^{ab}	19.8^{b}	21.3^{a}	0.58	18.3	18.5	18.4	0.37
Weaning[5]	12.7	12.8	14.2	0.50	13.7	13.4	13.9	0.34
Sow backfat change, mm								
d 106 to loading[2,6]	0.4	0.7	0.9	0.23	0.2	0.5	0.6	0.15
Loading[2] to weaning	-7.9	-6.9	-7.4	0.58	-4.6	-4.8	-4.5	0.38
d 106 to weaning	-7.2	-6.2	-6.3	0.56	-4.4	-4.4	-3.9	0.37

[1] A total of 467 sows were used from d 106 of gestation until weaning. Sows were weighed, blocked by BW and parity category, and allotted to regimen on d 106 of gestation. Regimens consisted of: 1) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 2.7 kg/d lactation feed (28 g SID Lys and 9.4 Mcal ME) until parturition; 2) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition; or 3) 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) from d 107 of gestation until parturition. Movement from gestation to farrowing occurred at d 113 (± 2 d) of gestation. Weaning occurred at d 18 to 24 of lactation.

[2] Time of movement from gestation to farrowing room (d 113 ± 2).

[3] Significant regimen within parity differences. Values within parity category without a common superscript differ ($P < 0.05$).

[4] Main effect of regimen ($P < 0.05$).

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[5] Main effect: Control vs. d 107, d 107 vs. d 113 ($P < 0.05$).

[6] Main effect: Control vs. d 113 ($P < 0.05$).

Table 2-3 Increased lysine and energy feeding duration prior to parturition on litter performance to 24 h within parity category[1]

	Gilts				Sows			
Response	Control	d 113	d 107	SEM	Control	d 113	d 107	SEM
Litter weight, kg								
Total born[2], 0 h	19.0^{b}	20.0^{a}	20.0^{a}	0.38	21.5^{ab}	21.2^{b}	22.0^{a}	0.24
Born alive[2], 0 h	16.7^{b}	18.0^{a}	17.8^{a}	0.31	20.4^{ab}	20.2^{b}	21.0^{a}	0.24
24 h[2]	17.5^{b}	18.7^{a}	18.4^{ab}	0.36	20.8	20.8	21.5	0.27
Mean piglet BW, g								
Total born[2], 0 h	1,289^{b}	1,362^{a}	1,356^{a}	26.3	1,479	1,507	1,463	16.8
Born alive[2], 0 h	1,308^{b}	1,403^{a}	1,388^{a}	23.7	1,470	1,458	1,508	18.1
24 h	1,435	1,503	1,489	25.4	1,586	1,585	1,618	18.6
Litter gain 0 to 24 h of live pigs, kg	1.28	1.07	1.07	0.171	1.23	1.40	1.17	0.095
Litter gain[3], kg	0.81	0.54	0.56	0.247	0.33	0.74	0.42	0.161
Total born birth weight CV, %	22.2	19.3	22.0	1.29	23.7	23.0	23.7	0.84
Born alive birth weight CV[2], %	18.4^{b}	16.1^{a}	16.4^{b}	0.83	20.0	19.4	19.9	0.53
Litter size at birth								
Total born, n	13.9	14.1	13.6	0.44	15.4	15.3	14.8	0.28
Born alive, %	92.8	93.9	94.3	1.03	92.8	93.1	94.0	0.71
Stillborn, %	7.3	6.1	5.7	1.14	7.2	6.9	6.0	0.70
Litter size at 24 h, n	12.3	12.8	12.3	0.52	13.5	13.1	13.7	0.35
Survival from birth to 24 h[4], %	96.0	97.1	96.6	0.86	95.0	95.3	96.1	0.59
Survivability to 24 h[5], %	89.2	91.1	91.4	1.21	88.3	89.1	90.5	0.87

[1] A total of 467 sows were used from d 106 of gestation until weaning. Sows were weighed, blocked by BW and parity category, and allotted to regimen on d 106 of gestation. Regimens consisted of: 1) Control: 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 2.7 kg/d lactation feed (28 g SID Lys and 9.4 Mcal ME) until parturition; 2) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition; or 3) 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) from d 107 of gestation until parturition. Movement from gestation to farrowing ocurred at d 113 (± 2 d) of gestation. Weaning occurred at d 18 to 24 of lactation.

[2] Significant regimen within parity differences. Values within parity category without a common superscript differ ($P < 0.05$).

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[3] Litter gain = (litter weight at 24 h) – (born alive litter birth weight).

[4] Survival from birth to 24 h = litter size at 24 h/ born alive.

[5] Survivability to 24 h = (total born-(stillborn +24h mortality))/total born.

Table 2-4 Increased lysine and energy feeding duration prior to parturition on litter performance to weaning within parity category[1]

	Gilts				Sows			
Response	Control	d 113	d 107	SEM	Control	d 113	d 107	SEM
Litters, n	42	43	41	--	99	98	100	--
Litter weight, kg								
After cross foster[2]	19.8	20.2	20.5	0.39	20.9	21.4	21.6	0.33
Weaning[5]	73.2	71.6	70.4	1.55	76.2	78.3	77.4	1.20
Average piglet BW, kg								
After cross foster[2]	1.48	1.52	1.54	0.029	1.56	1.60	1.61	0.025
Weaning [5]	5.98	6.00	5.80	0.105	6.57	6.54	6.56	0.082
Litter gain[3,4,5], kg	54.0^{a}	51.5^{ab}	49.7^{b}	1.61	55.2	57.0	55.7	1.05
Litter count, n								
After cross foster[2]	13.3	13.5	13.3	0.56	13.6	13.2	13.7	0.36
Weaning	12.3	12.1	12.2	0.54	11.7	11.9	11.9	0.34
Fallbacks[6], %	2.9	2.9	2.4	0.66	5.3	3.7	4.9	0.63
Mortality[4,7], %	5.0	7.5	5.1	1.14	8.1^{a}	5.4^{b}	7.1^{ab}	0.79
Weaned[4,8], %	92.4	90.2	92.0	1.33	86.6^{b}	90.9^{a}	88.3^{b}	1.06
Wean age, d	20.8	20.9	20.7	0.23	20.8	20.6	20.6	0.15

[1] A total of 423 sows were weaned from an initial 472 sows that farrowed. Sows were removed due to poor milking, health challenge, becoming nurse sows. Pigs stayed with birth sow until 24 h, then were cross-fostered within regimen to equalize litter size. Regimens consisted of: 1) Control: 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 2.7 kg/d lactation feed (28 g SID Lys and 9.4 Mcal ME) until parturition; 2) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition; or 3) 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) from d 107 of gestation until parturition. Movement from gestation to farrowing occurred at d 113 (± 2 d) of gestation. Weaning occurred at d 18 to 24 of lactation.

[2] Piglets were cross-fostered within regimen between 24 and 48 h. Weights are adjusted to reflect the addition or subtraction of fostered piglets.

[3] Litter gain = Litter weaning weight – litter weight after cross foster.

[4] Significant regimen within parity differences. Values within parity category without a common superscript differ ($P < 0.05$).

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[5] Count after cross-foster used as a covariate.

[6] Fallbacks were pigs removed due to weight loss or injury and moved to a nurse sow. This occurred between d 3 and d 10 of age, and is divided by the litter count after cross-fostering.

[7] Mortality that occurred after cross-fostering until weaning. Does not include mortality in the first 24 h.

[8] Percentage weaned = litter count at weaning/litter count after cross foster.

Table 2-5 Increased lysine and energy feeding duration prior to parturition on colostrum quality and yield within parity category[1]

	Gilts				Sows			
Response	Control	d 113	d 107	SEM	Control	d 113	d 107	SEM
Count, n	46	46	45	--	113	110	112	--
Fat,[2] %	5.4	5.4	5.3	0.21	4.7[a]	4.6[ab]	4.4[b]	0.13
Protein,%	14.8	14.9	15.1	0.27	15.3	14.9	15.1	0.17
Solids,[2] %	24.7	25.3	25.1	0.36	24.6[a]	24.1[ab]	24.0[b]	0.22
Lactose, %	3.2	3.1	3.2	0.05	3.1	3.2	3.2	0.03
IgG,[3] mg/mL	107	125	105	1.6	114	131	126	1.3
Colostrum yield,[4,6] kg	5.35	5.37	5.28	0.23	5.99	6.13	6.02	0.13
Colostrum intake,[5,6] g	445	437	436	17.0	461	480	460	11.0

[1] A total of 467 sows were used from d 106 of gestation until weaning Regimens consisted of: 1) Control: 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 2.7 kg/d lactation feed (28 g SID Lys and 9.4 Mcal ME) until parturition; 2) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition; or 3) 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) from d 107 of gestation until parturition. Movement from gestation to farrowing occurred at d 113 (± 2 d) of gestation. Weaning occurred at d 18 to 24 of lactation. Fifty mL of colostrum was collected within 3 h from the onset of parturition from multiple teats. Samples were sent to a commercial laboratory (Stearns DHIA Lab, Sauk Centre, MN) and analyzed in duplicate for fat, protein, lactose, and total solids (Combi-Foss milk analyzer, Foss Analytics, Denmark). Immunoglobulin G concentration was analyzed in duplicate using the porcine colostrum immunoglobin G (IgG) ELISA Quantitation Kit (Bethyl Laboratories, Montgomery, TX).

[2] Significant regimen within parity differences. Values within parity category without a common superscript differ ($P < 0.05$).

[3] Main effect of regimen: control vs. d 113 ($P < 0.05$).

[4] Total colostrum intake for the litter.

[5] Average colostrum intake of a piglet calculated as: -106 + 2.26 WG + 200 BWB + 0.111 D - 1,414 WG/D + 0.0182 WG/BWB, where WG is 24 h piglet weight gain in grams, D is duration of colostrum suckling in minutes, and BWB is body weight at birth.

[6] Pig:teat ratio used as a covariate.

Table 2-6 Increased lysine and energy feeding duration prior to parturition on subsequent reproductive performance within parity category[1]

	Gilts				Sows			
Response	Control	d 113	d 107	SEM	Control	d 113	d 107	SEM
Sows, n	42	43	41	--	99	98	100	--
Wean to estrus interval, d	5.0	5.0	5.3	0.59	4.9	4.9	4.9	0.35
In estrus by d 7, %	86.2	88.4	90.0	5.81	94.8	93.8	96.0	2.45
Farrowing rate, %	92.1	80.0	87.5	6.34	90.8	90.8	91.3	3.01
Litters, n	33	33	35	--	86	89	91	--
Subsequent litter								
Total born, n	13.5	13.6	14.5	0.64	14.9	15.8	15.7	0.41
Born alive, %	96.2	93.3	95.0	1.27	91.6	92.8	93.5	0.86
Stillborn, %	3.2	4.8	2.9	1.06	6.6	6.2	4.9	0.75
Mummified, %	0.6	1.9	2.2	0.66	1.8	0.9	1.6	0.38

[1] A total of 423 sows were recorded for a wean to estrus interval, and 363 sows from that group had subsequent farrowing data. Regimens consisted of: 1) Control: 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 2.7 kg/d lactation feed (28 g SID Lys and 9.4 Mcal ME) until parturition; 2) 2.0 kg/d gestation feed (12.5 g SID Lys and 6.5 Mcal ME) until d 113 of gestation, then 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) until parturition; or 3) 3.8 kg/d lactation feed (40 g SID Lys and 13.3 Mcal ME) from d 107 of gestation until parturition. Weaning occurred at d 18 to 24 of lactation.

Chapter 3 - Effects of timing and size of meals prior to farrowing on sow and litter performance

ABSTRACT

A total of 727 mixed parity (μ= 3.8) sows were used to evaluate the effects of timing and size of meals before farrowing on sow and litter performance. Upon entry to the farrowing house (d 113), sows were blocked by weight within parity and allotted to 1 of 3 feeding management strategies until farrowing: 1) 2.7 kg lactation diet (1.15% standardized ileal digestible lysine and 2,153 Kcal/kg net energy) once daily at 0700 h; 2) 4 daily meals of 0.67 kg (0100 h, 0700 h, 1300 h, 1900 h); 3) ad libitum lactation diet and encouraged to consume feed at 0100 h, 0700 h, 1300 h, and 1900 h. After farrowing all sows were provided lactation diet ad libitum until weaning. Data was analyzed for treatment effects within parity category in a mixed model with block as a random effect. Feeding sows ad libitum before farrowing tended to reduce sow body weight loss (*P* = 0.077) and reduce backfat loss (*P* = 0.003) from entry into the farrowing house until weaning compared to sows fed 4 daily meals, with sows fed once daily intermediate. Litter gain from 24 h to weaning tended to be greater (*P* = 0.073) in sows fed ad libitum or 4 times daily prior to farrowing compared to sows fed one meal. Piglet weaning weight increased (*P* = 0.050) in sows fed ad libitum before farrowing, compared to those fed one meal, with those fed 4 times daily intermediate. There was no evidence for difference in farrowing duration, stillborn rate, colostrum yield, or 24 h piglet survival regardless of treatment. However, from 24 h after farrowing to weaning, sows fed one daily meal prior to farrowing had an increased (*P* = 0.012) percentage of fall-behind pigs compared to sows fed ad libitum, and increased (*P* = 0.027) preweaning mortality compared to sows fed four daily meals, resulting in reduced (*P* = 0.006) weaned percentage compared to sows fed four daily meals. There was no evidence for difference

(*P* > 0.10) in subsequent reproductive performance regardless of treatment. In conclusion, when sows were fed ad libitum from 2 to 3 days before farrowing there was an observed improvement in sow body weight and backfat maintenance during lactation, and piglet weaning weight during lactation. Increased frequency of meals prior to farrowing improved the survival of pigs to weaning compared to sows fed a single meal prior to farrowing.

INTRODUCTION

The time from initiation to completion of parturition has naturally increased as genetic selection increased litter size by 0.2 pigs per year over the past three years (Stalder, 2018). Longer farrowing durations can have negative effects on sow health and survival of piglets during parturition and lactation. Increased farrowing duration has been associated with a greater number of stillbirths (Oliviero et al., 2010; Feyera et al., 2018). This is likely due to long farrowing process causing hypoxia of piglets resulting in stillbirths, or negatively impacting live born piglet growth and survivability beyond the first few hours of life (Herpin et al., 1996). It remains unknown if increased farrowing duration is caused by stillborn piglets blocking the birth canal, if the sow has depleted her energy stores during parturition and slows contractions, or if other genetic and environmental factors are resulting in increased farrowing duration (Vanderhaeghe et al., 2013).

Recent data from a commercial sow study demonstrated that on average, parturition lasts for 4 hours, but can range from 30 minutes up to 12 hours to complete (Gourley et al., 2019). Feyera et al. (2018) conducted a retrospective analysis to evaluate the timing of the last meal prior to parturition on farrowing duration and stillborn rate. They concluded that when sows had been offered a meal 3 hours or less before parturition, she had a shorter farrowing duration, decreased need for farrowing assistance, and reduced stillborn rate, in comparison to sows that had been offered their last meal greater than 6 h prior to farrowing. They hypothesized that this was due to higher plasma glucose levels at the onset of farrowing which resulted in more energy to be readily available during the farrowing process. Oliviero et al. (2009) observed longer farrowing durations were associated with a number of factors including sow housing, sow backfat, sow constipation score, and number of stillborn pigs. Several peripartum feeding strategies have been investigated to reduce farrowing duration and stillborn rate with little to no benefit observed (Vallet et al., 2013; Manu et al., 2018; van den Bosch et al., 2019).

Currently, commercial farms utilize many different feeding management strategies once sows are moved into farrowing crates until the onset of parturition such as feeding one set feed amount in the morning, feeding two smaller meals twice daily, ad libitum, or other combinations. To our knowledge, no previous study has focused specifically on number of meals, and feed availability from d 113 of gestation to parturition, and its effect on farrowing duration and piglet survival. Therefore, the objective of this study was to determine the effect of amount of feed and frequency of feed delivery on the parturition process, sow and litter performance, and survivability of piglets.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. A total of 727 sows (Fast Large white × PIC Landrace) were used at a commercial sow farm in southern Minnesota (New Fashion Pork, Jackson, MN). During gestation, sows were housed in individual stalls. The farrowing house was equipped with individual crates each containing a shelf feeder with a hopper for sows, nipple waterer for sows, and heat mat for piglets. On the day of gestation when sows entered the farrowing house (d 113 ± 2), sows were weighed and backfat (**BF**) was measured at the P2 position (Renco Lean Meter, S.E.C. Repro Inc., Quebec, Canada). At this time, sows were blocked by body weight (**BW**) within parity category (gilts, parity 1, and parity 2+) and allotted to 1 of 3 feeding management strategies. Treatments consisted of: 1) sows fed 2.7 kg lactation diet once daily at 0700 h; 2) sows fed a total of 2.7 kg lactation diet in 4 daily 0.68 kg meals (0100 h, 0700 h, 1300 h, 1900 h); and 3) sows were offered ad libitum lactation diet (ensured at least 2.5 kg of diet in the feeder) and encouraged to consume meals 4 times daily by making the sows stand (0100 h, 0700 h, 1300 h, 1900 h). When sows entered the farrowing house (1300 h), treatments 2 and 3 were fed their first meal, whereas treatment 1 did not receive their first meal in the farrowing house until the following morning. Prior to entry to the farrowing house, sows were fed 2.04 kg of gestation diet in a single daily meal offered at 0700 h. Diets were formulated to meet or exceed nutrient requirements (Table 1) and were manufactured at the New Fashion Pork feed mill (Estherville, IA). Feed samples were collected twice each week from the feeders at the farm. Samples were pooled and used for chemical analysis.

All feeding strategies were administered via hand feeding from a feed cart equipped with a scale until the start of parturition. At the start of parturition, feed remaining in the feeder was weighed to calculate total feed consumed from entry to the farrowing house until parturition. Sows were not fed during parturition; however, upon completion, sows were fed lactation diet ad libitum until weaning. Pre-farrow feed intake was recorded for all individual sows and on a subsample of 310 sows during lactation.

During parturition, sows were continuously monitored for 24 h. When a piglet was born, time was recorded, pigs were dried off using a desiccant (Tech dry; Techmix LLC., Stewart, MN) and paper towels. Umbilical cords were then tied and cut to approximately 10 cm in length. Additionally, pigs were given an individual ear tag for identification and weighed before placing them next to the sow. Stillborn and mummified fetuses were also weighed and birth time recorded. During parturition, farrowing assistance was provided after 30 to 45 min with no farrowing progress evidence from the time a previous was pig born. When provided, farrowing assistance was noted on the litter record. The farrowing process was complete when no new pig had been born after 1 h and placenta expulsion observed. At 24 h after birth of the first piglet in each litter, piglets were individually weighed to calculate colostrum intake and colostrum yield. All piglets remained with their birth sow during the trial until weaning.

Sow blood glucose was measured on a subsample of 345 sows. Blood was obtained by pricking the ear auricular vein with a needle, and using a Glucometer (AimStrip Plus, Germaine Laboratories Inc., San Antonio, TX) to measure blood glucose. Measurements were collected at three time points during parturition: start of farrowing, 2 h after start of farrowing, and at the end of farrowing.

All piglet mortalities prior to 24 hours were recorded and classified as either 1) died at birth (died within an hour of birth) or 2) laid on (due to crushing by the sow). Due to the health status of the farm, no cross-fostering occurred, and no nurse sows were utilized. At 24 h, piglets less than 600 g were identified and euthanized according to farm protocol. Fall-behind pigs and mortalities were weighed, and date was recorded for all litters from birth to weaning. Fall-behind piglets were classified as losing weight for multiple days during lactation or sustaining a life-threatening injury; they were removed from the sow and humanely euthanized (Euthanex AgPro; Nutriquest; Mason City, IA).

On the day prior to weaning, all piglets were individually weighed to measure litter growth and litter weight CV. On the day of weaning (d 21± 3), sows were weighed, and BF was measured at the P2 position. Sows were moved to individual gestation stalls and checked once daily for signs of estrus using a boar and back pressure test for 42 d post-farrowing. Wean to first service interval and d 30 conception rate were collected on a total of 562 sows that remained after culling due to age (n=160), injury (n=3), or infertility (n=2). Farrowing rate, subsequent total born, born alive, and stillborn were collected by farm employees and accessed through the farm database (PigCHAMP; Ames, IA).

Calculations

Sow BW post-farrowing was calculated by subtracting the weight of conceptus from sow BW at d 113. Weight of conceptus was calculated for each sow using the equations described by Thomas et al. (2018), using the variables: total born, average piglet birth weight, and gestation length. Piglet birth weight CV, 24 h weights and weaning weights were calculated from using individual pig weights within each litter at each time point.

Colostrum intake for individual piglets was calculated using the equation developed by Theil et al. (2014a), using piglet 24 h weight gain, suckling duration, and birth weight. Colostrum yield for each sow was calculated as the sum of the colostrum intake of the pigs in the litter. If a piglet died before 24 h, the assumption was that there was no colostrum intake by that piglet.

Time from loading into farrowing crates to the onset of farrowing was calculated as (date of farrowing – date of entry to farrowing house), in days. Time consuming meals prior to farrowing was calculated as (start time of parturition - time the first meal was delivered upon entry to the farrowing house), in hours. Time since last meal was calculated as (farrow start time

– time of last meal), in minutes. Pig to teat ratio for each sow was calculated as number of born alive piglets divided by functional teats. Pre-farrow feed intake is the sum of feed consumed from entry to the farrowing house until the start of parturition. Total feed intake is total pre-farrow feed intake plus total lactation feed intake. Farrowing duration was calculated as the time from birth of first pig to birth of last pig. Average birth interval per sow was calculated as the actual interval between each piglet and then averaged for the sow. Percentage assisted was calculated by dividing the number of pigs sleeved per litter by the number of total born pigs per litter.

Chemical Analysis

A total of 8 samples (1 per week) of lactation diet from within the weekly pooled samples were sent to a commercial laboratory (Table 1; Ward Laboratories, Kearney, NE). Samples were analyzed in duplicate for crude protein (AOAC 990.03, 2006), Ca (Campbell and Plank, 1991; Kovar, 2003), and P (Campbell and Plank, 1991; Kovar, 2003).

Statistical Analysis

Data were analyzed using generalized linear mixed models where dietary treatment within parity category was a fixed effect, with random effect of block. Heterogeneous variance by treatment was tested for each variable and used if it significantly improved the model fit.

Sow BW, backfat depth, litter weights, mean piglet BW, litter gain, colostrum yield and intake, piglet BW CV, total born, litter counts, and feed intake were fit using a normal distribution. Farrowing duration and birth interval were log transformed to normalize data and then fit using a normal distribution. Wean to estrus interval was fit using a negative binomial distribution. Percentage born alive, stillborn, assisted, survived to 24 h, fall-behind, mortality, weaned, in estrus by d 7, conception rate and farrowing rate were fit using a binomial distribution.

Covariates were used if they significantly improved the model fit. Residuals and the Bayesian Information Criterion were used as an indication of improved model fit. Entry weight was used as a covariate for sow weaning weight, sow entry backfat, and weight change from entry to weaning. Sow backfat at entry was used as a covariate for sow backfat at weaning and backfat change from entry to weaning. Parity was used as a covariate for total sow feed intake. Total born was used as a covariate for total born litter weight, and total born, born alive and 24 h mean piglet BW, and total born individual pig weight CV. Born alive was used as a covariate for born alive and 24 h litter weights and CV. Both lactation length and born alive were used as a covariate for litter weaning weight and mean piglet weaning weight. Pig to teat ratio was used as a covariate for litter gains, colostrum yield, and colostrum intake. Sow blood glucose was analyzed for a time × treatment interaction, and main effects of time and treatment using a repeated measures statement. Statistical models were fit using the Lme function (lmer package of R, version 3.5.2). Results were considered significant at $P < 0.05$ and marginally significant at $0.05 \leq P < 0.10$.

RESULTS

Timing of treatments

Time from loading to farrowing was 0.3 days shorter ($P = 0.005$) for sows fed ad libitum prior to farrowing, compared to sows that received one meal daily (Table 2). Time consuming meals prior to farrowing (in hours) was shorter ($P = 0.001$) for sows fed 2.7 kg once daily compared to the other two treatments, as would be expected due to feeding strategy design of the trial. As a result, time since last meal in relation to start of parturition decreased (*P* = 0.001) in sows fed 0.68 kg or ad libitum and made to stand every 6 hours compared to those fed 2.7 kg once daily. Total pre-farrow feed intake was increased (*P* = 0.001) in sows fed ad libitum compared to the other feeding strategies. These results validated that the feeding strategies had been applied successfully, in order to create differences in timing of meals and amount of feed provided prior to parturition.

Sow body weight, back fat, and feed intake

There was no evidence sow BW and BF were different (*P* > 0.10) at the start of the trial (entry to the farrowing house). Calculated sow BW post-farrowing was similar (*P* > 0.10), which was expected due to no change in weight of conceptus from dietary treatments applied for 3 d prior to farrowing. Sow BW at weaning was marginally heavier (*P* = 0.077) in sows that had been fed ad libitum prior to farrowing compared to those fed 0.68 kg every 6 h. As a result, sows that consumed feed ad libitum prior to farrowing had reduced sow BW loss from post-farrow to weaning (*P* = 0.035) and tended to have reduced sow BW loss from entry to weaning (*P* = 0.077) compared to those fed 0.68 kg every 6 h, with sows fed 2.7 kg once daily intermediate. Sow BF loss during lactation was reduced (*P* = 0.003) in sows fed ad libitum compared to sows fed 0.68 kg every 6 h, resulting in greater (*P* = 0.003) BF at weaning in sows fed ad libitum prior to farrowing, compared to sows fed 0.68 kg every 6 h, with sows fed 2.7 kg once daily intermediate.

Sow lactation feed intake was numerically increased (*P* = 0.175) in sows fed ad libitum prior to farrowing (5.1 vs. 4.8 kg/d) compared to sows fed 2.7 kg once daily, with those fed 0.68 kg every 6 h intermediate. Combining lactation feed intake with pre-farrow feed intake resulted in increased (*P* = 0.018) total feed intake per sow for sows fed ad libitum prior to farrowing compared to sows fed 2.7 kg once daily, with those fed 0.68 kg every 6 h intermediate.

Farrowing duration and piglet survivability

There was no evidence total born pigs and percentage of pigs born alive or stillborn were different (*P* > 0.10) due to feeding strategy (Table 3). There were differences (*P* < 0.001) in percentage of pigs assisted per sow. The sows fed ad libitum prior to farrowing, had the highest percentage assistance, followed by sows fed once daily prior to farrowing, with those receiving 0.68 kg every 6 h having the lowest assistance rate. Farrowing duration, birth interval, and time to birth of 6th pig were similar (*P* > 0.05) across feeding strategies (Table 4).

Percentage of pigs that died at birth or were laid on within 24 h after birth were similar (*P* > 0.10) across treatments, which resulted in no evidence for difference (*P* > 0.10) in piglet survival to 24 h. Piglets that were euthanized at 24 h due to low birth weight, or injury were similar (*P* = 0.110) across treatments. Percentage of fall behind pigs was reduced (*P* = 0.012) in sows fed ad libitum prior to farrowing compared to those fed once daily prior to farrowing, with those fed 0.68 kg every 6 h prior to farrowing intermediate. Piglet mortalities from 24 h to weaning were reduced (*P* = 0.027) in sows fed 0.68 kg every 6 h compared to those fed once daily prior to farrowing. Although litter size at weaning was similar across treatments, the total percentage of pigs weaned was increased (*P* < 0.05) in those fed 0.68 kg every 6 h prior to farrowing compared to those restricted to 2.7 kg once daily, with ad libitum fed sows intermediate.

Litter performance and colostrum production

Feeding strategies prior to farrowing did not influence (*P* = 0.122) total born litter weight. Born alive litter weight was heavier (*P* = 0.046) in sows fed 0.68 kg every 6 h compared to the control, with sows fed ad libitum intermediate. There was no evidence for difference (*P* > 0.10) in colostrum yield or intake, which resulted in similar 24 h litter weights and litter gain in the first 24 h. Litter weight at weaning and litter gain from 24 h to weaning was marginally increased (*P* < 0.10) in sows fed 0.68 kg every 6 h or ad libitum prior to farrowing compared to those fed 2.7 kg once daily.

Mean piglet BW was marginally greater (*P* = 0.055) in total born pigs and greater (*P* = 0.045) in born alive pigs in sows fed 0.68 kg every 6 h prior to farrowing compared to those fed 2.7 kg once daily, with those fed ad libitum prior to farrowing intermediate. This resulted in marginally increased (*P* = 0.088) piglet weights at 24 h in sows fed 0.68 kg every 6 h compared to the other two treatments. At weaning, pigs from sows fed ad libitum prior to farrowing were heavier (*P* = 0.050) compared to sows fed 2.7 kg once daily prior to farrowing, with those fed 0.68 kg every 6 h intermediate. There was no evidence for difference (*P* > 0.10) in CV for piglet BW at birth, 24 h, or weaning, regardless of feeding strategy.

Sow blood glucose and subsequent reproductive performance

There was no evidence for a treatment × time point interaction in sow blood glucose (Figure 1). A feeding strategy main effect was observed where sows fed ad libitum had the greatest (*P* = 0.003) blood glucose concentrations at each time point (start of farrowing, 2 h after start of farrowing, and at the end of farrowing), sows fed 0.68 kg every 6 hours had the lowest blood glucose concentrations, with sows fed 2.7 kg once daily intermediate. Additionally, a main effect of time was observed, where blood glucose concentrations increased (*P* = 0.001) from the start of farrowing to the end of farrowing.

After culling at weaning, a total of 562 females remained in the herd and were used to measure subsequent reproductive performance (Table 5). There was no evidence for difference

(*P* > 0.10) in wean-to-estrus interval, percentage of females in estrous by d 7 or 20 after weaning, conception rate, or farrowing rate regardless of feeding strategy prior to farrowing. Subsequent total born, born alive, and stillborn were similar (*P* > 0.10) across all pre-farrow feeding strategies.

DISCUSSION

Farrowing duration, stillborn rate, and farrowing assistance

In 2017, the average percentage of stillbirths and mummified fetuses in U.S. sow herds was 9.8% (Stalder, 2018). It has been observed that longer farrowing duration is associated with increased piglet asphyxia and stillborn rate (Langendijk and Plush, 2019). There was no evidence for difference in stillborn rate or farrowing duration in the current study, regardless of feeding amount or meal frequency prior to farrowing. In contrast, Feyera et al. (2018) observed an increase in the probability of stillbirths when the time from last meal to parturition exceeded 6 h compared to those that had received feed less than 6 h before farrowing. These different results may be due to the difference in average farrowing duration, farrowing assistance, total born or dietary energy supplied in the pre-farrow period between studies. In the present study, farrowing duration averaged 3.5 h, which is much shorter than the average 5.8 h observed by Feyera et al. (2018). Total born was also lower in the present study (16.0 vs. 17.1 pigs) compared to Feyera et al (2018). We speculate that the lower total born in the present study resulted in a shorter mean farrowing duration, therefore limiting the number of sows experiencing farrowing fatigue due to pre-farrow fasting. Farrowing assistance was more frequent in the present study which may have reduced the differences in stillbirths between treatments, whereas Feyera et al. (2018) allowed up to a 60 min birth interval before intervention. Additionally, sows in the current study would have received 8.9 to 11.0 Mcal/d metabolizable energy (**ME**) prior to farrowing compared to only 7.4 Mcal/d ME provided the last 3 d prior to farrowing by Feyera et al. (2018). The increased dietary energy provided in the current study pre-farrow may have reduced the impact of time from last meal prior to farrowing on farrowing duration, as previously observed (Feyera et al., 2018).

Interestingly, a difference in the percentage of pigs assisted was highest in sows fed ad libitum prior to farrowing, and lowest in sows fed small meals every 6 h prior to farrowing. This result would suggest that increased frequency and a smaller meal size prior to farrowing had a positive impact on the sow's ability to expel piglets without assistance, which would be similar to observations by Feyera et al. (2018). Although sows fed ad libitum were encouraged to consume a meal every 6 h prior to farrowing and had 24 h access to feed, perhaps they ate fewer large meals and had not consumed a meal as frequently as those that were restricted to 0.68 kg every 6 h. Indeed, Guillemet et al. (2010) noted that sows prefer to work for food compared to ad libitum access, which demonstrates a change in feeding behavior when sows receive free access to feed.

Piglet survivability and colostrum production

Our current study demonstrated that feeding frequency and feed quantity had little observable impact on piglet survival in the first 24 h since the percentage of pigs that were crushed or died at birth were similar across treatments. The improvement in piglet survival became evident from 24 h to weaning as the number of mortalities was reduced in sows fed every 6 h prior to farrowing compared to sows fed one daily meal prior to farrowing. This could be explained in part by the heavier average piglet birth weight (1.29 vs 1.24 kg) improving survival to weaning, which is well established (Baxter et al., 2008; Oliviero et al., 2019).

Furthermore, Neil (1996) observed reduced pre-weaning mortality in sows that were fed ad libitum 4 d prior to farrowing compared to sows restricted fed until d 3 postpartum. The improved survival in the current study may be attributed to increased pig birth weight, improved milk output resulting in increased weaning weights, or a combination of multiple factors. Piglet characteristics related to survival are often interrelated, thus it is difficult to determine a single variable responsible for improved piglet survival (Baxter et al., 2008; Theil et al., 2014b). However, these results suggest feeding strategy prior to parturition may have an impact in the sows' ability to raise her piglets to weaning.

Colostrum intake and yield were similar, indicating that feed amount or timing did not impact colostrum production in the short period prior to farrowing. In contrast, Mallmann et al. (2019) observed a decrease in colostrum yield when gilts were fed increasing amounts of gestation feed starting on d 90 of gestation. The authors concluded that the restricted fed gilts (1.8 kg/d) were mobilizing body protein and backfat to meet demands for fetal growth and colostrum production prior to farrowing, with fat mobilization being prioritized for colostrum yield, therefore allowing for greater colostrum production in restricted-fed gilts. Because sow nutrient intake was not restricted to the severity as studied by Mallmann et al. (2019), sows in the current study likely mobilized minimal body protein and lipid stores to meet the colostrum demands if they were below the peripartum requirements as suggested by Dourmad et al. (2008).

Sow BW and BF change

Lactation BW and BF loss was reduced when sows had consumed lactation feed ad libitum from entry to farrowing compared with sows fed 4 meals daily of 0.68 kg. Reduced BW and BF loss has also been observed in several studies where sows began ad libitum feed intake the last few days prior to farrowing (Neil, 1996; Cools et al., 2014; Decaluwe et al., 2014). The reduction in BF and BW loss is likely a result of increased feed consumption during the peripartum period (9.7 vs. 7.9 kg) and improved feed intake during the lactation period when sows were fed ad libitum. It is important to note that ad libitum feed intake prior to farrowing did not exceed 7 d. In previous studies that evaluated ad libitum or increased feeding strategies starting on d 90 of gestation, excess BW and BF gain occurred which contributed to decreased feed intake and increased sow body lipid mobilization in lactation (Weldon et al., 1994; Goncalves et al., 2016; Mallmann et al., 2019). These results suggest that feeding duration of a high energy and lysine diet may be largely responsible for the differences in sow body store mobilization and feed intake, and perhaps a short feeding duration with high feed intake peripartum is in fact beneficial to lactation performance.

Sow feed intake

Lactation feed intake increased numerically in the present study in sows that were fed ad libitum compared to those restricted to one meal daily. Similarly, Decaluwe et al. (2014) observed a tendency for increased feed intake from d 108 of gestation through weaning in sows that had been fed three 1.5 kg meals/d prior to parturition compared to those receiving 1.5 kg daily. This change in feed intake could be due to a change in feeding behavior by allowing sows to determine their feed intake prior to farrowing, rather than restricted feeding. Cools et al. (2014) observed that peripartum voluntary feed intake was almost twice as much in sows fed ad libitum compared to sows restricted fed. Moreover, ad libitum feed allowance introduced 4 d prior to farrowing improved total lactation feed intake compared to those restricted until farrowing or 5 d after farrowing (Neil, 1996), and minimized BW and BF loss compared to sows restricted fed until 5 d after farrowing. These studies would be in contrast to results from an earlier study where primiparous sows were fed ad libitum from d 60 of gestation and had reduced lactation feed intake compared to sows that had been restricted fed in gestation (Weldon et al., 1994). Increased feed intake for an extended period of time can alter insulin sensitivity leading to suppressed lactation feed intake (Weldon et al., 1994). This further supports the idea that length of time that sows are offered ad libitum feed intake prior to farrowing can dictate the results of lactation feed intake.

Litter performance

The increase in average pig birth weight when sows were fed 0.68 kg every 6 h in the present study was unexpected. Because the feeding amount was the same in sows fed 0.68 kg every 6 h and fed 2.7 kg once daily, the increase in pig birth weight is not from an increase of total nutrients offered each day, but could be a factor of numerically lower litter size (15.7 vs. 16.0 or 16.1 total born) or changes in blood glucose. Several studies observed no change in litter weight or average pig birth weight when feeding sows ad libitum 4 to 7 d prior to farrowing (Neil, 1996; Cools et al., 2014; Decaluwe et al., 2014). In contrast, supplying gilts with 40 g standardized ileal digestible lysine and 13.3 Mcal ME from d 107 or 113 of gestation until farrowing increased piglet birth weight in gilts (Gourley et al., 2019). These different results may be attributed to the difference in parity, where older parity sows do not appear to partition additional energy consumed towards fetal growth (NRC, 2012). Nevertheless, additional research should be conducted to confirm if the number of meals offered pre-farrowing will improve performance compared to a single meal offering the same total daily nutrients.

The improvement in weaning weights observed from sows fed ad libitum prior to farrowing could have been a result of numerically higher lactation feed intake increasing milk production. As lactation feed intake is increased, milk output and litter growth increase (Hansen, 2012; Strathe et al., 2017). In the current study, it may be suggested that sows consuming feed ad libitum prior to farrowing were pre-conditioned to eat larger meals and transitioned more rapidly to consuming feed ad libitum in lactation compared to sows restricted fed prior to farrowing. In support of this, Guillemet et al. (2010) observed a quicker transition to lactation diets when sows were fed a high fiber (12.8% crude fiber) during gestation compared to a low fiber diet (3.5% crude fiber). The increase in lactation diet intake may be a factor of already consuming a greater amount of feed during gestation to maintain similar net energy to sows with low fiber diets. Therefore, feed intake in the last few days prior to parturition may not have an impact on birthweight, but rather is beneficial for establishing a level of feed intake that supports increased milk production and concomitantly litter growth throughout lactation.

Sow blood glucose

The range in sow blood glucose at the onset of farrowing was similar to previous studies (Le Cozler et al., 1999; Feyera et al., 2018). The increase in sow blood glucose as farrowing duration increased suggests that sows will begin gluconeogenesis to support the uterine demands for energy near the end of parturition. Le Cozler et al. (1999) observed sow arterial glucose concentration remained constant as time since birth of first piglet increased, and rapidly increased after the birth of the last pig until time of placenta expulsion. This may be due an increased demand of glucose as a precursor for lactose in milk synthesis once parturition is complete (Farmer et al., 2015), or circulating hormones during parturition altering glucose regulation. Feyera et al. (2018) demonstrated glucose and triglyceride extraction by the uterus increased 1.4 and 6-fold, respectively, 8during parturition compared to after parturition. This may explain the rapid increase in arterial glucose following parturition, due to a decreased demand by the gravid uterus after the last pig is expelled.

The differences in blood glucose between treatments at all three timepoints are consistent, where sows fed ad libitum prior to farrowing had the highest blood glucose and sows fed 0.68 kg every 6 h had the lowest blood glucose. Similar to humans, it appears that increased frequency of meals may have reduced circulating blood glucose levels due to improved glucose tolerance (Carlson et al., 2007). This may benefit lactation feed intake as evidenced by a numerical improvement in feed intake observed in sows fed 4 daily meals compared to sows fed a single meal prior to farrowing. Long term, reduced glucose tolerance in late gestation may be a sign of gestational diabetes as reported by Kemp et al. (1996). However, due to differences in farrowing timing in relation to a consumed meal, it is unknown whether a sow was fasted prior to the start of farrowing, which may have increased the variability in initial glucose concentration we measured. Furthermore, Kemp et al. (1996) observed a weak correlation between sows with decreased fasting blood glucose on d 104 and increased piglet birthweights. This is in contrast to data suggesting that high blood glucose typically results in heavier birthweights (Vambergue and Fajardy, 2011). These conflicting results demonstrate more understanding of blood glucose effects on birth weight are needed in this area in swine.

Subsequent reproductive performance

No change in subsequent reproductive or litter characteristics were observed regardless of feeding strategy prior to farrowing. It has been observed that if sows mobilize greater than 12% of body protein during lactation, there will be reduced embryo survival (Vinsky et al., 2006) and decreased subsequent farrowing rate (Clowes et al., 2003). Although there were differences in sow BW change (μ = -4.0%) and BF change (μ = -14.8%) during lactation, it appears they were not great enough to elicit a negative effect in subsequent reproductive performance. In the present study a limited number of first parity sows were used due to the parity distribution of the sow herd, therefore further research is needed to determine if these same results would occur in first parity sows. Previous research suggests first parity sows may have improved subsequent reproductive performance when fed increased lysine and energy prior to farrowing (Gourley et al., 2019).

Implications

In summary, it is important to consider the length of time of ad libitum feeding prior to farrowing, where the benefits in lactation feed intake, reduction in backfat loss and improvements in litter growth can be observed. Feeding sows ad libitum lactation diet for an average of 3 d prior to farrowing increased weaning weight compared to sows fed once daily prior to farrowing. Sows limit-fed 4 times daily prior to farrowing had increased weaned percentage compared to sows fed one meal daily prior to farrowing. With levels of sow productivity in this study, there was no evidence feeding strategies from entry to the farrowing house until parturition impacted farrowing duration, birth interval, or stillborn rate. As litter size continues to increase, nutritional or management strategies to help reduce farrowing duration and improve piglet survival to weaning should continue to be investigated.

LITERATURE CITED

AOAC International. 2006. Official methods of analysis of AOAC International. 15th ed. AOAC Int., Gaithersburg, MD.

Baxter, E. M., S. Jarvis, R. B. D'Eath, D. W. Ross, S. K. Robson, M. Farish, I. M. Nevison, A. B. Lawrence, and S. A. Edwards. 2008. Investigating the behavioural and physiological indicators of neonatal survival in pigs. Therio. 69:773-783. doi: 10.1016/j.theriogenology.2007.12.007

Campbell, C. R. and C. O. Plank. 1991. Sample Preparation. In: C. O. Plank, editor, Plant analysis reference procedures for the southern region of the United States. Southern Cooperative Series Bulletin #368. p. 1-11.

Carlson, O., B. Martin, K. S. Stote, E. Golden, S. Maudsley, S. S. Najjar, L. Ferrucci, D. K. Ingram, D. L. Longo, W. V. Rumpler, D. J. Baer, J. Egan, and M. P. Mattson. 2007. Impact of reduced meal frequency without caloric restriction on glucose regulation in healthy, normal-weight middle-aged men and women. Metab. 56:1729-1734. doi: 10.1016/j.metabol.2007.07.018

Clowes, E. J., F. X. Aherne, G. R. Foxcroft, and V. E. Baracos. 2003. Selective protein loss in lactating sows is associated with reduced litter growth and ovarian function. J. Anim. Sci. 81:753-764. doi: 10.2527/2003.813753x

Cools, A., D. Maes, R. Decaluwe, J. Buyse, T. A. van Kempen, A. Liesegang, and G. P. Janssens. 2014. Ad libitum feeding during the peripartal period affects body condition, reproduction results and metabolism of sows. Anim. Reprod. Sci. 145:130-140. doi: 10.1016/j.anireprosci.2014.01.008

Decaluwe, R., D. Maes, A. Cools, B. Wuyts, S. De Smet, B. Marescau, P. P. De Deyn, and G. P. Janssens. 2014. Effect of peripartal feeding strategy on colostrum yield and composition in sows. J. Anim. Sci. doi: 10.2527/jas2014-7612

Dourmad, J.-Y., M. Étienne, A. Valancogne, S. Dubois, J. van Milgen, and J. Noblet. 2008. InraPorc: A model and decision support tool for the nutrition of sows. Anim. Feed Sci. Tech. 143:372-386. doi: 10.1016/j.anifeedsci.2007.05.019

Farmer, C., N. L. Trottier, and J. Y. Dourmad. 2015. Mammary blood flow and nutrient uptake. In: C. Farmer, editor, The pregnant and lactating sow. Wageningen Academic Publishers, Wageningen, The Netherlands. p. 319-331.

Feyera, T., T. F. Pedersen, U. Krogh, L. Foldager, and P. K. Theil. 2018. Impact of sow energy status during farrowing on farrowing kinetics, frequency of stillborn piglets, and farrowing assistance. J. Anim. Sci. 96:2320-2331. doi: 10.1093/jas/sky141

Goncalves, M. A. D., S. S. Dritz, M. D. Tokach, J. H. Piva, J. M. DeRouchey, J. C. Woodworth, and R. D. Goodband. 2016. Fact sheet increased late gestation feed intake. J. Swine Health Prod. 24:264-266.

Gourley, K. M., A. J. Swanson, J. C. Woodworth, J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, and B. Frederick. 2019. 183 Effects of increasing duration of feeding high dietary lysine and energy prior to farrowing on sow and litter performance under commercial conditions. J. Anim. Sci. 97(Suppl. 2):103-104 (Abstr.) doi: 10.1093/jas/skz122.183

Guillemet, R., C. Guerin, F. Richard, J. Y. Dourmad, and M. C. Meunier-Salaun. 2010. Feed transition between gestation and lactation is exhibited earlier in sows fed a high-fiber diet during gestation. J. Anim. Sci. 88:2637-2647. doi: 10.2527/jas.2009-2307

Hansen, A. V. 2012. Feed intake in reproducing sows. In: K. E. B. Knudsen, N. J. Kjeldsen, H. D. Poulsen and B. B. Jensen, editors, Nutritional Physiology of Pigs: with Emphasis on Danish Production Conditions. Landbrug and Fodevarer.

Herpin, P., J. Le Dividich, J. C. Hulin, M. Fillaut, F. De Marco, and R. Bertin. 1996. Effects of the level of asphyxia during delivery on vability at birth and early postnatal vitality of newborn pigs. J. Anim. Sci. 74:2067-2075. doi: 10.2527/1996.7492067x

Kemp, B., N. M. Soede, P. C. Vesseur, F. A. Helmond, J. H. Spoorenberg, and K. Frankena. 1996. Glucose tolerance of pregnant sows is related to postnatal pig mortality. J. Anim. Sci. 74:879-885. doi: 10.2527/1996.744879x

Kovar, J. L. 2003. Method 6.3 Inductively coupled plasma spectroscopy. In: J. Peters, editor, Recommended methods of mature analysis publication A3769. Univ. of Wisconsin Extension, Madison, WI. p. 41-43.

Langendijk, P., and K. Plush. 2019. Parturition and its relationship with stillbirths and asphyxiated piglets. Animals. 9:885. doi: 10.3390/ani9110885

Le Cozler, Y., V. Beaumal, M. Neil, C. David, and J. Y. Dourmad. 1999. Changes in the concentrations of glucose, non-esterifed fatty acids, urea, insulin, cortisol and some mineral elements in the plasma of the primiparous sow before, during and after induced parturition. Reprod. Nutr. Dev. 39:161-169. doi: 10.1051/rnd:19990201

Mallmann, A. L., E. Camilotti, D. P. Fagundes, C. E. Vier, A. P. G. Mellagi, R. R. Ulguim, M. L. Bernardi, U. A. D. Orlando, M. A. D. Goncalves, R. Kummer, and F. P. Bortolozzo. 2019. Impact of feed intake during late gestation on piglet birth weight and reproductive performance: a dose-response study performed in gilts. J. Anim. Sci. 97:1262-1272. doi: 10.1093/jas/skz017

Manu, H., D. Pangeni, P. Wilcock, and S. K. Baidoo. 2018. The effect of superdosing phytase from 109 days of gestation through lactation on farrowing duration, piglet and sow performance. J. Anim. Sci. 96 (Suppl. 2):148. (Abstr.) doi: 10.1093/jas/sky073.273

Neil, M. 1996. Ad libitum lactation feeding of sows introduced immediately before, at, or after farrowing. Anim. Sci. 63:497-505. doi: 10.1017/s1357729800015393

NRC. 2012. Nutrient Requirments of Swine. 11th ed. Natl. Acd. Press, Washington, DC.

Oliviero, C., M. Heinonen, A. Valros, and O. Peltoniemi. 2010. Environmental and sow-related factors affecting the duration of farrowing. Anim. Repro. Sci. 119:85-91. doi: 10.1016/j.anireprosci.2009.12.009

Oliviero, C., S. Junnikkala, and O. Peltoniemi. 2019. The challenge of large litters on the immune system of the sow and the piglets. Reprod. Domest. Anim. 54 (Suppl. 3):12-21. doi: 10.1111/rda.13463

Oliviero, C., T. Kokkonen, M. Heinonen, S. Sankari, and O. Peltoniemi. 2009. Feeding sows with high fibre diet around farrowing and early lactation: Impact on intestinal activity, energy balance related parameters and litter performance. Res. Vet. Sci. 86:314-319. doi: 10.1016/j.rvsc.2008.07.007.

Stalder, K. J. 2018. Pork industry productivity analysis, National Pork Board, Des Moines, IA.

Strathe, A. V., T. S. Bruun, and C. F. Hansen. 2017. Sows with high milk production had both a high feed intake and high body mobilization. Animal. 11:1913-1921. doi: 10.1017/S1751731117000155

Theil, P. K., C. Flummer, W. L. Hurley, N. B. Kristensen, R. L. Labouriau, and M. T. Sorensen. 2014a. Mechanistic model to predict colostrum intake based on deuterium oxide dilution technique data and impact of gestation and prefarrowing diets on piglet intake and sow yield of colostrum. J. Anim. Sci. 92:5507-5519. doi: 10.2527/jas2014-7841

Theil, P. K., C. Lauridsen, and H. Quesnel. 2014b. Neonatal piglet survival: impact of sow nutrition around parturition on fetal glycogen deposition and production and composition of colostrum and transient milk. Animal. 8:1021-1030. doi: 10.1017/S1751731114000950

Thomas, L. L., R. D. Goodband, M. D. Tokach, S. S. Dritz, J. C. Woodworth, and J. M. DeRouchey. 2018. Partitioning components of maternal growth to determine efficiency of feed use in gestating sows. J. Anim. Sci. 96:4313-4326. doi: 10.1093/jas/sky219

Vallet, J. L., J. R. Miles, and L. A. Rempel. 2013. Effect of creatine supplementation during the last week of gestation on birth intervals, stillbirth, and preweaning mortality in pigs. J. Anim. Sci. 91:2122-2132. doi: 10.2527/jas.2012-5610

Vambergue, A., and I. Fajardy. 2011. Consequences of gestational and pregestational diabetes on placental function and birth weight. World. J. Diabetes. 2:196-203. doi: 10.4239/wjd.v2.i11.196

van den Bosch, M., J. Wijnen, I. B. van de Linde, A. A. M. van Wesel, D. Melchior, B. Kemp, H. van den Brand, and C. Clouard. 2019. Effects of maternal dietary nitrate supplementation on farrowing and placental characteristics, level of asphyxiation at birth and piglet vitality. Therio. 129:1-7. doi: 10.1016/j.theriogenology.2019.01.033

Vanderhaeghe, C., J. Dewulf, A. de Kruif, and D. Maes. 2013. Non-infectious factors associated with stillbirth in pigs: a review. Anim. Reprod. Sci. 139:76-88. doi: 10.1016/j.anireprosci.2013.03.007

Vinsky, M. D., S. Novak, W. T. Dixon, M. K. Dyck, and G. R. Foxcroft. 2006. Nutritional restriction in lactating primiparous sows selectively affects female embryo survival and overall litter development. Reprod. Fert. Dev. 18:347-355. doi: 10.1071/rd05142

Weldon, W. C., A. J. Lewis, G. F. Louis, J. L. Kovar, M. A. Giesemann, and P. S. Miller. 1994. Postpartum feeding hypophagia in primiparous sows: I. Effects of gestation level on feed intake, feeding behavior, and plasma metabolite concentrations during lactation. J. Anim. Sci. 72:387-394. doi: 10.2527/1994.722387x

Table 3-1 Dietary Composition[1]

Ingredient, %	Lactation diet
Ground corn	46.30
Dried distillers' grain with solubles	25.00
Soybean meal, 47.5% CP	21.3
Vegetable oil blend[2]	2.85
Limestone	1.38
Monocalcium phosphate, 21% P	0.93
Liquid energy[3]	0.75
L-Lysine HCl	0.52
Salt	0.28
Vitamin premix[4]	0.25
L-Threonine	0.17
Choline Chloride, 60%	0.10
L-Valine	0.06
L-Methionine	0.05
L-Tryptophan	0.03
Standardized ileal digestible amino acids, %	
Lysine	1.15
Methionine and cysteine:lysine	0.50
Threonine:lysine	0.65
Tryptophan:lysine	0.18
Valine:lysine	0.70
Isoleucine:lysine	0.56
Total lysine, %	1.30
Crude protein, %	20.1
Metabolizable energy, kcal/kg	3,320
Net energy, kcal/kg	2,535
Calcium, %	0.77
Phosphorus, %	0.66
Analyzed composition[5], %	
Dry matter	89.5
Crude protein	20.6
Calcium	1.06
Phosphorus	0.67

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[1] Lactation diets were fed upon entry to farrowing house, according to treatment feeding strategy. After farrowing, sows received lactation diet ad libitum until weaning.

[2] Build R2 (Feed Energy Company, Pleasant Hill, IA)

[3] XFE Liquid Energy; alcohol-based liquid product (XFE Products, Des Moines, IA)

[4] Provided per kg diet: 10,409 IU vitamin A; 447 IU vitamin D_3; 36.3 µg vitamin D; 70 IU vitamin E; 250 mg vitamin C; 3.7 mg vitamin K; 41.4 mg niacin; 27.5 mg Pantothenic acid; 1.7 mg Folic acid; 2.1 mg Thiamine; 8.1 mg Riboflavin; 4 mg Pyridoxine; 35.4 mg vitamin B_{12}; 0.4 mg Biotin; 221 mg Fe from Fe sulfate; 0.3 mg Se from Na selenite; 18.5 mg Cu from Intelibond C; 132 mg Zn from Intelibond Z; 33 mg Mn from Mn oxide; 1.2 I from calcium iodate; 0.44 mg Cr from Cr propionate; 500 FTU phytase.

[5] A total of 8 samples (1 per week) of lactation diet from within the weekly pooled samples were analyzed in duplicate at a commercial laboratory (Ward Laboratories, Kearney, NE).

Table 3-2 Timing and amount of feed delivered to sows prior to farrowing on sow performance[1]

Response	2.7 kg × 1 delivery	0.68 kg × 4 deliveries	Ad libitum × 4 deliveries	SEM	*P*-value
Count, n	242	245	240	--	--
Parity, n	3.8	3.8	3.9	--	--
Gestation length, d	115.5	115.5	115.4	0.08	0.323
Lactation length[2], d	21.7	21.7	21.9	0.09	0.043
Time from loading to farrow[3], d	3.2^{a}	3.1^{ab}	2.9^{b}	0.08	0.005
Time consuming meals prior to farrow[4], h	57.4^{b}	70.9^{a}	65.1^{a}	1.94	0.001
Time from last meal to farrrowing[5], min	605^{a}	196^{b}	216^{b}	25.6	0.001
Sow BW, kg					
Entry	260.3	259.7	260.2	1.78	0.734
Post farrow[6]	247.2	245.9	245.9	1.75	0.237
Weaning	237.7	236.1	239.4	1.10	0.077
Sow weight change, kg					
Entry to weaning	-23.8	-25.4	-22.1	1.10	0.077
Post farrow-weaning	-10.7^{ab}	-11.4^{b}	-8.4^{a}	0.94	0.035
Sow backfat, mm					
Entry	13.4	13.8	14.0	0.24	0.179
Weaning	11.6^{ab}	11.1^{b}	11.8^{a}	0.16	0.003
Sow backfat change, mm					
Entry to weaning	-2.2^{ab}	-2.7^{a}	-1.9^{b}	0.16	0.003
Sow Feed intake					
Total pre-farrow feed intake[7], kg	7.5^{b}	7.9^{b}	9.7^{a}	<0.31[10]	0.001
Lactation average daily feed intake[8], kg	4.8	5.0	5.1	0.09	0.175
Total feed intake[9], kg	116.0^{b}	117.8^{ab}	123.8^{a}	<3.50[11]	0.018

[1] A total of 727 mixed parity sows were used from entry into the farrowing house (d 113 ± 2 of gestation) until weaning. Sows were weighed, blocked by parity category and weight, and allotted to treatment at time of entry to the farrowing house. Treatments consisted of 1) Sows fed 2.7 kg lactation diet once daily at 0700 h; 2) sows fed 2.7 kg lactation diet 4 times daily in 0.68 kg meals (0100 h, 0700 h, 1300 h, 1900 h); and 3) sows fed ad libitum lactation diet and encouraged to consume meals every 4 times daily (0100 h, 0700 h, 1300 h, 1900 h). Weaning occurred on d 21.7 (± 3.3 d) of lactation.

[2] Tukey adjustment resulted in no mean separation.

[3] Days spent in farrowing crate prior to parturition = (Farrowing date – load date).

[4] Number of hours sow received treatments prior to farrowing. Sows were loaded into farrowing crates at 1300 h each day, therefore sows consuming 0.68 kg meals and ad libitum received feed at loading. Sows receiving 2.7 kg once a day did not receive feed until the following morning.

[5] Time from last meal delivery to the birth of first pig.

[6] Calculated from equation by Thomas et al (2018).

[7] Sum of feed consumed from loading to farrowing, measured on all sows.

[8] Lactation feed intake was measured on a subsample of 310 sows.

[9] Sum of feed consumed from loading to weaning, measured on a subsample of 310 sows.

[10] Heterogenous variance by treatment, SEM = 0.23, 0.25, and 0.31 for sows receiving 2.7 kg × 1 delivery, 0.68 kg × 4 deliveries, and ad libitum × 4 deliveries, respectively.

[11] Heterogenous variance by treatment, SEM = 3.47, 3.50, and 3.33 for sows receiving 2.7 kg × 1 delivery, 0.68 kg × 4 deliveries, and ad libitum × 4 deliveries, respectively.

Table 3-3 Timing and amount of feed delivered to sows prior to farrowing on litter performance[1]

Response	2.7 kg × 1 delivery	0.68 kg × 4 deliveries	Ad libitum × 4 deliveries	SEM	*P*-value
Litter Characteristics					
Total Born, n	16.1	15.7	16.0	0.23	0.351
Born alive, %	93.4	93.8	93.6	0.45	0.664
Stillborn, %	6.6	6.1	6.4	0.44	0.667
Assisted, %	16.1^{b}	13.7^{c}	19.6^{a}	1.11	0.001
Litter size at 24 h, n	13.9	13.6	13.8	0.20	0.432
Litter size at weaning, n	11.2	11.3	11.2	0.15	0.752
Litter weight, kg					
Total born, 0h	19.4	20.0	19.4	0.20	0.053
Born alive, 0h	18.2^{b}	18.7^{a}	18.3^{ab}	0.19	0.046
24 h	18.7	19.2	18.9	0.21	0.219
Weaning[2]	53.1	55.2	54.1	0.65	0.083
Mean piglet BW, kg					
Total born, 0h	1.24	1.28	1.25	0.012	0.055
Born alive, 0h	1.25^{b}	1.29^{a}	1.26^{ab}	0.013	0.045
24 h	1.36	1.40	1.37	0.012	0.088
Weaning[2]	4.80^{b}	4.90^{ab}	4.94^{a}	0.045	0.050
Litter gain 0 to 24 h, kg	1.38	1.27	1.29	0.048	0.218
Litter gain 24 h to wean, kg	34.08	35.94	35.26	<0.620[6]	0.073
CV of individual pig weights, %					
Total born	23	22	23	0.40	0.218
24 h	23	22	23	0.40	0.143
Weaning[2]	19	19	19	0.40	0.486
Colostrum intake[3], g/pig	418	422	415	<6.0[7]	0.606
Colostrum yield[4] kg/sow	5.7	5.7	5.6	0.08	0.471
Pig:teat[5]	0.98	0.97	0.98	0.015	0.832

[1] A total of 727 mixed parity sows were used from entry into the farrowing house (d 113 ± 2 of gestation) until weaning. Sows were weighed, blocked by parity category and weight, and allotted to treatment at time of entry to the farrowing house. Control sows were fed 2.7 kg lactation diet once daily at 0700 h; sows were fed 2.7 kg lactation diet 4 times daily in 0.68 kg meals (0100 h, 0700 h, 1300 h, 1900 h); sows were fed ad libitum lactation diet and encouraged to consume meals every 4 times daily (0100 h, 0700 h, 1300 h, 1900 h).

[2] Lactation length averaged 21.7 ± 3.3 d.

[3] Calculated based on equation from Theil et al. (2014a).

[4] Sum of individual colostrum intake for all pigs in the litter.

[5] Pigs per functional teat.

[6] Heterogenous variance by treatment, SEM = 0.620, 0.534, and 0.535 for sows receiving 2.7 kg × 1 delivery, 0.68 kg × 4 deliveries, and ad libitum × 4 deliveries, respectively.

[7] Heterogenous variance by treatment, SEM = 5.3, 6.0, and 5.2 for sows receiving 2.7 kg × 1 delivery, 0.68 kg × 4 deliveries, and ad libitum × 4 deliveries, respectively.

Table 3-4 Timing and amount of feed delivered to sows prior to farrowing on farrowing duration, birth order and survival[1]

Response	2.7 kg × 1 delivery	0.68 kg × 4 deliveries	Ad libitum × 4 deliveries	SEM	*P*-value
Farrowing duration[2], min	209	200	214	1.16	0.226
Birth interval, min	13.6	13.7	14.3	1.07	0.448
Birth time of 6th pig, min	90.2	93.1	95.5	3.82	0.620
Outcome to 24 h[3]					
Died at birth[4], %	1.3	1.5	1.3	0.22	0.839
Laid on, %	5.0	5.2	5.2	0.41	0.950
Survived to 24 h, %	93.6	93.3	93.4	0.44	0.912
Outcome to weaning[3]					
Euthanized at 24 h, %	2.5	2.1	2.8	0.31	0.110
Fall-behind, %	7.5^{a}	6.3^{ab}	5.9^{b}	0.52	0.012
Dead, %	7.6^{a}	6.1^{b}	6.6^{ab}	0.49	0.027
Weaned, %	74.3^{b}	77.6^{a}	76.1^{ab}	0.80	0.006

[1] A total of 727 mixed parity sows were used from entry into the farrowing house (d 113 ± 2 of gestation) until weaning. Sows were weighed, blocked by parity category and weight, and allotted to treatment at time of entry to the farrowing house. Treatments consisted of 1) Sows fed 2.7 kg lactation diet once daily at 0700 h; 2) sows fed 2.7 kg lactation diet 4 times daily in 0.68 kg meals (0100 h, 0700 h, 1300 h, 1900 h); and 3) sows fed ad libitum lactation diet and encouraged to consume meals every 4 times daily (0100 h, 0700 h, 1300 h, 1900 h). Weaning occurred on d 21.7 (± 3.3 d) of lactation.

[2] Time from birth of first piglet to last piglet.

[3] Calculations use the count of the variable divided by born alive count. Analyzed as a binominal.

[4] Died within an hour after birth, includes low viable, deformed and savaged pigs.

Table 3-5 Timing and amount of feed delivered to sows prior to farrowing on subsequent reproductive performance[1]

Response	2.7 kg × 1 delivery	0.68 kg × 4 deliveries	Ad libitum × 4 deliveries	SEM	*P*-value
Count, n	188	188	186	--	--
Wean to estrus interval[2], d	4.6	4.0	4.3	<0.182[3]	0.162
Estrous by d 7, %	95.7	96.3	96.2	1.47	0.958
Estrous by d 20, %	97.3	99.4	98.9	1.17	0.204
Conception rate[4], %	89.4	88.3	86.6	2.51	0.703
Farrowing rate[5], %	85.1	87.8	85.0	2.62	0.673
Subsequent litter					
Count[6], n	160	165	158	--	--
Total born, n	13.7	14.0	13.7	0.26	0.492
Born alive, %	93.4	93.3	92.8	0.55	0.809
Stillborn, %	6.6	6.7	7.2	0.59	0.809

[1] A total of 562 mixed parity sows remaining in the herd were used to collect subsequent reproductive performance. Sows were culled after lactation due to old age (n=160), injury (n=3), or infertile (n=2).

[2] Sows were monitored for 42 d after weaning for signs of estrus.

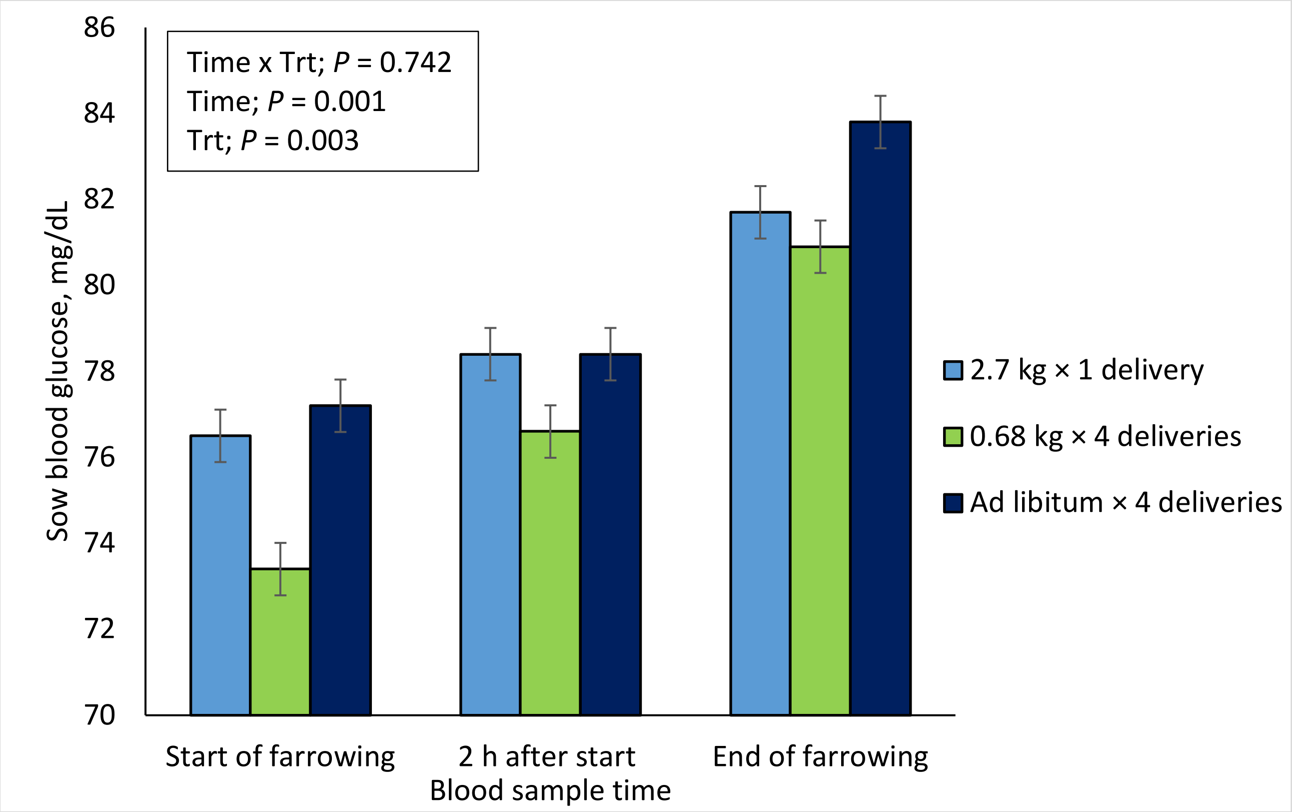
[3] Heterogenous variance by treatment, SEM = 0.18, 0.17, and 0.17 for sows receiving 2.7 kg × 1 delivery, 0.68 kg × 4 deliveries, and ad libitum × 4 deliveries, respectively.

[4] Sows confirmed pregnant at d 30 divided by total number bred.

[5] Sows farrowed divided by total number bred.

[6] Sows that farrowed a subsequent litter.

Figure 3-1 Effect of feeding strategy on sow blood glucose measurements[1]



[1] A subsample of 345 mixed parity sows were used for blood glucose measurement. Blood glucose was measured by pricking the ear vein and using a glucometer to read the glucose concentration (mg/dL) at three time points during parturition. End of farrowing was characterized as no new piglets for 45 minutes and evidence of placenta expulsion.

Chapter 4 - Sow and piglet traits associated with piglet survival at birth and to weaning

ABSTRACT

Understanding the relationship between sow and piglet characteristics that are associated with stillborn rate and pre-weaning mortality is beneficial as litter size continues to increase. Two experiments were previously conducted to evaluate pre-farrowing nutrition regimens on sow and litter characteristics. These two datasets (Exp. 1 and 2) were then used to identify sow and piglet characteristics associated with stillborn rate and piglet survival to weaning. A total of 1,201 sows that gave birth to 19,168 pigs comprised the dataset. The following characteristics were used in multivariate logistic regression analysis for traits associated with stillborn rate or survival to weaning: parity, litter weight, mean piglet birth weight, sow backfat and body weight at d 113 of gestation, gestation length, farrowing duration, litter size, piglet birth order, farrowing assistance, pig to teat ratio, colostrum intake and colostrum yield. Sows within each experiment (herd) were categorized into quartiles for each of the independent variables to quantify the relationship to stillborn rate or survival to weaning. Increased stillborn rate was associated ($P < 0.01$) with heavier litter weights, lighter piglet birth weights, and larger litters in both experiments. In Exp. 1, increased stillborn rate was associated ($P < 0.01$) with longer farrowing duration. Increased stillborn rate was associated with sows with less backfat depth at d 113, older parity, or increased farrowing assistance in Exp. 2. In both experiments, pigs born later in the birth order had an increased ($P < 0.01$) risk of being stillborn. In both experiments, heavier piglet birth weight, greater colostrum intake and lower total born were associated ($P < 0.01$) with increased survival to weaning. In Exp. 2, pigs born in the first 75% of the litter, or in a litter with lower pig to teat ratio were associated ($P < 0.01$) with increased survival to weaning. Although the stillborn rate was similar between experiments (6.5 vs. 6.6%), differences in the traits associated with stillborn rate between studies indicate that some associated traits may be herd dependent. However, improving piglet birthweight, placing an emphasis on assisting pigs born later in the birth order and increasing colostrum intake will increase piglet survival from birth to weaning.

INTRODUCTION

Currently in U.S. swine herds, stillborn and mummified fetuses represent 9.8% of total born pigs, while pre-weaning mortality is 17.8% on average (Stalder, 2018). Therefore, over 25% of total born pigs do not survive to weaning. This represents both an economic cost and a welfare concern for the swine industry. Stillborn pigs are typically a result of hypoxia due to successive contractions constricting the umbilical cord (Alonso-Spilsbury et al., 2005), which increases stillbirth rate for those piglets born later in the farrowing process. Typically, longer farrowing duration is associated with an increased stillborn prevalence (Theil, 2015). Several studies have reported longer farrowing duration is associated with litter size, sow constipation score, and time since last meal prior to farrowing (van Dijk et al., 2005; Feyera et al., 2018; Langendijk and Plush, 2019). Even if a piglet is live born, it is estimated that 15 to 20% are hypoxic at birth which could impact piglet survival in the first 24 h and to weaning. Hypoxic piglets have reduced suckling response leading to reduced colostrum intake and poor temperature homeostasis (Langendijk and Plush, 2019).

Although several reviews and studies have focused on areas associated with stillborn rate and pre-weaning mortality, little data is available that associated piglet survival at birth and at weaning to sow and piglet traits that could be easily measured or influenced by management or nutrition (van Dijk et al., 2005; Rootwelt et al., 2012; Udomchanya et al., 2019). Furthermore, these studies are typically conducted in research settings with small sample sizes (Panzardi et al., 2013; Nuntapaitoon et al., 2018).

Therefore, the objective of the present study was to evaluate individual sow and piglet records from two commercial sow research studies to: 1) identify sow characteristics associated with increased stillborn rate; 2) identify piglet characteristics associated with being a stillborn pig; and 3) identify sow and piglet characteristics that are associated with piglet survival to weaning.

MATERIALS AND METHODS

The results presented in the current paper are based on data from two independent studies that evaluated the effects of peripartum feeding strategies on piglet survival, colostrum production, and litter performance (Gourley et al., 2020a; 2020b). The two studies were conducted on commercial sow farms in southern Minnesota. Sows were individually housed in environmentally controlled and mechanically ventilated barns and were fed corn-soybean meal-based diets during gestation and lactation.

Study population

Experiment 1

Data was collected from May to August 2018. Sows were fed 2 kg of gestation diet until d 107, at which time dietary feeding strategies were imposed until farrowing as previously described (Gourley et al., 2020a), then fed lactation diet ad libitum until weaning (20.7 d ± 1.6). The study used 473 sows (Large White × Landrace; parity 1.7 ± 1.6) that gave birth to 7,154 pigs (6,458 live-born and 481 stillborn). Mummified fetuses (n = 215) were excluded from the analysis and total born calculations. Litters (n = 11) with total born of 6 or fewer were not used in the analysis. Piglets remained with their birth sow until 24 h post-farrowing, then were cross fostered within dietary treatments to equalize litter size.

Experiment 2

Data was collected from May to August 2019. Sows were fed 2 kg of gestation diet until entry to farrowing house (d 113 ± 1.7), at which time dietary feeding strategies were imposed until farrowing as previously described (Gourley et al., 2020b), then fed lactation diet ad libitum until weaning (21.7 d ± 3.3). The study used 728 sows (Fast Large White × PIC Landrace; parity 3.9 ± 1.7) that gave birth to 12,014 pigs (10,758 live-born and 817 stillborn), where mummified fetuses (n = 439) were excluded from the analysis and total born calculations. Litters (n = 8) with total born of 5 or fewer were not used in the analysis. No piglets were cross-fostered and, thus, all pigs remained with birth sow until weaning.

Sow management and recordings around farrowing

For both experiments, sows were housed in individual stalls from d 0 to d 113 of gestation, then moved to an individual farrowing stall. Sows were weighed and backfat was measured (P2 position; Renco Lean-Meter; S.E.C. Repro Inc., Quebec, Canada) upon entry into the farrowing house at approximately d 113 of gestation.

Sows were supervised daily around farrowing for signs of parturition. Once parturition began, each farrowing was monitored to record birth time, birth weight, birth order and classify piglets as born alive, stillborn, or mummified fetus. Farrowing assistance was given to sows if the birth interval exceeded 30 to 45 minutes from the previous piglet birth with no evidence of farrowing progress. Piglets were classified as born alive if they physically moved or took a breath immediately after birth. Stillborn piglets were classified as fully formed piglets with the absence of a detectable heartbeat at birth. Mummified fetuses were recorded but excluded from the total born calculation. Live born piglets were individually identified with an ear tag. All live born pigs were individually reweighed at 24 h after the birth of the first pig in the litter. Colostrum intake per pig and sow colostrum yield was calculated using the equation from Theil et al. (2014). Piglet mortalities between birth and weaning were recorded on an individual pig basis, with the day of death, dead weight, and individual pig identification recorded.

Calculations

Total born is a summation of born alive and stillborn pigs. Farrowing assistance was recorded as assisted or unassisted for each sow. Farrowing duration was considered the time from birth of first pig until the last pig was expelled from the sow. Birth order ranking (0 to 100) was calculated as [(birth order-1)/(total born-1) × 100], to standardize for differences in litter size. The first pig born in each litter was assigned rank 0 and the last pig born was assigned the rank 100. Pig to teat ratio was calculated by dividing born alive pigs by the number of functional teats per sow, where a number greater than 1 means there were more pigs nursing than teats available.

Statistical analysis

Each herd was analyzed separately due to differences in the population studied. Data was first analyzed for characteristics related to stillborn rate. Stillborn rate was considered the dependent variable and analyzed as a binomial variable with the numerator being number of stillborn pigs and denominator being number of total born pigs per sow. Two separate models were utilized to analyze stillborn rate either including or removing litter weight as a covariate, as it is confounded with litter size. Piglet survivability to weaning was analyzed as a binomial, where number of pigs weaned was the numerator and number of total born pigs per sow was the denominator. All data was analyzed using R statistical program (Version 3.5.2).

Experiment 1

For characteristics related to stillborn rate two separate models (including or removing litter weight as a covariate) were used which included either 8 or 9 independent variables (parity, litter weight, average pig birth weight, d 113 backfat, d 113 body weight, gestation length, dietary treatment, farrowing duration, and farrowing assistance) were included in a multivariate logistic regression model to evaluate which variables were related to stillborn rate. Stepwise elimination based on improving Bayesian information criterion **(BIC),** where the model with the lowest BIC is preferred, was used to determine the final model which included the variables: litter weight or d 113 sow BW, piglet birth weight and farrowing duration. Quartiles of each variable were derived to create categorical responses. To analyze for differences in stillborn rate between quartiles of each respective variable, a generalized linear model for a binomial response was fit, with a Tukey adjustment for multiple comparisons used for mean separation between quartiles.

Experiment 2

For characteristics related to stillborn rate two separate models (including or removing litter weight as a covariate) were used which included 10 or 11 variables (parity, litter weight, average pig birth weight, d 113 backfat, d 113 body weight, gestation length, time since last meal pre-farrow, feed amount d 113 to farrow, farrowing duration, farrowing assistance, and oxytocin use) were included in a multivariate logistic regression model to evaluate which variables were related to stillborn rate. Stepwise elimination based on improving BIC was used to determine the final model which included the 5 variables of: litter weight or d 113 sow BW, piglet birth weight, sow backfat, farrowing assistance, and parity. Quartiles of each variable were derived to create categorical responses. To analyze for differences in stillborn rate between quartiles of each respective variable, a generalized linear model for a binomial response was fit, with a Tukey adjustment for multiple comparisons used for mean separation between quartiles.

Piglet data

Because total born was used as the denominator in the logistic model, it was unable to be tested as a variable in the analysis for sow factors. Individual piglet data was used to analyze for effect of total born and birth order on stillborn rate in both experiments. For survivability to weaning, individual piglet data was used to analyze for the effect of total born, birth order, colostrum intake, and pig to teat ratio. A binary response was used to test the relationship of stillborn or survival to weaning and the variables birth order, total born, and colostrum intake with piglet as the experimental unit. Similar to the analysis of sow data, quartiles were used to categorize the piglet population for each response variable.

RESULTS

The herd in Exp. 1 was younger (1.7 vs. 3.9 parity), heavier conditioned at d 113 (19.0 vs 13.8 mm backfat), farrowed fewer total born (14.8 vs. 15.9), and had heavier piglet birth weights (1,410 vs. 1,230 g) than the herd in Exp. 2 (Table 1). Regardless of the differences in population, the average born alive percentage (93.5 vs 93.4%) and stillborn rate (6.5 vs. 6.6%) were similar between the two herds. In addition, more females were studied in Exp. 2 compared to Exp. 1 (n = 728 vs. 473). When utilizing individual pig records for survival to weaning analysis, 4.8% of pig records (Exp. 1) and 1.6% of pig records (Exp. 2) were excluded from analysis due to missing weaning records.

Stillborn rate

Experiment 1

The first multivariate logistic regression model indicated that litter weights, average piglet birth weight, and farrowing duration were associated ($P < 0.001$) with stillborn rate in the sow population (Table 2). The second model, which did not include litter weight as a variable, indicated that sow body weight on d 113 of gestation, average piglet birth weight and farrowing duration were associated ($P < 0.001$) with stillborn rate in the sow population. Using quartiles to explain changes in stillborn rate among the different litter weight categories, litters weighing less than 18.1 kg had a lower ($P < 0.05$) stillborn rate compared to litters weighing greater than 21.3 kg, with the heaviest quartile (> 24 kg) having the highest ($P < 0.05$) stillborn rate compared to the lowest two quartiles (Table 3). Sows categorized in the lowest quartile for average pig birth weight (< 1,300 g) had the highest observed stillborn rate (8.8%) and it was greater ($P < 0.05$) than sows categorized in the two heaviest piglet birth weight quartiles (>1,430 g). Sows categorized in the lowest quartile for farrowing duration (< 162 min) had the lowest stillborn rate (4.5%), with stillborn rate increasing ($P < 0.05$) with each increase in quartile up to 9.3% stillborn pigs for sows categorized with farrowing durations longer than 308 minutes. Sows categorized with d 113 BW less than 266 kg were associated with a lower ($P < 0.05$) stillborn rate compared to sows with d 113 BW greater than 292 kg, with those with d 113 BW between 267 and 292 kg intermediate.

Individual piglet data was used to evaluate effect of birth order and total born on stillborn rate. As position in the birth order increased from first quartile to last quartile, percentage of stillborn pigs increased ($P < 0.05$) from 1.6% for pigs born in the first quarter of the litter to 18.7% for pigs born in the last quarter of the litter. As litter size category increased from first quartile (< 13 pigs) to third quartile (16 to 17 pigs) stillborn rate increased from 4.7 to 6.9%. Litters categorized in the highest total born quartile (> 17 pigs) had the highest ($P < 0.05$) stillborn rate (10.4%) compared to the other three quartiles.

Experiment 2

Similar to Exp. 1, two multivariate logistic regression models were used to evaluate stillborn rate. The first model indicated that litter weight, average piglet birth weight, sow backfat at d 113, farrowing assistance and parity were associated with stillborn rate. The second model indicated that sow BW on d 113 of gestation, average piglet birth weight, sow backfat at d 113, farrowing assistance and parity were associated with stillborn rate. Sows categorized with litters weighing greater than 22.4 kg observed a greater ($P < 0.05$) stillborn rate compared to litters weighing less than 16.9 kg, with sows in the middle two quartiles intermediate (Table 4). When sows were categorized according to average piglet birth weight, sows in the lowest quartile (< 1,100 g) had an increased ($P < 0.05$) stillborn rate compared to sows categorized with an average piglet birthweight greater than 1,250 kg, with sows in the heaviest quartile (> 1,400 g) having the lowest stillborn rate (5.4%). Sows categorized in the lowest quartile for backfat at d 113 of gestation (< 11 mm) had an increased ($P < 0.05$) stillborn rate compared to sows categorized in the heaviest two quartiles (> 14 mm backfat), with those categorized with 11 to 13 mm backfat intermediate. Sows categorized in the lowest quartile for d 113 BW (< 244 kg) had reduced ($P < 0.05$) stillborn rate compared to sows in the highest two quartiles (> 262 kg), with sows weighing between 244 and 261 kg at d 113 intermediate. Sows categorized as parity 3 or younger had a lower ($P > 0.05$) stillborn rate compared to sows categorized as parity 4 or greater, with sows categorized as parity 5 or older having the highest stillborn rate (8.6%). Sows categorized as receiving farrowing assistance observed a higher ($P < 0.05$) stillborn rate compared to sows with no assistance (5.0 vs. 7.6%).

Individual piglet data was used to evaluate birth order and total born as predictors of stillborn rate. The lowest quartile for total born (< 14 pigs) observed the lowest ($P < 0.05$) stillborn rate (4.7%) compared to the highest two quartiles (>17 pigs). Pigs categorized in the middle quartile (14 to 16 total born pigs) had a lower ($P < 0.05$) stillborn rate compared to pigs in litters with greater than 18 total born. Pigs categorized as born in the first quarter of the litter observed the lowest ($P < 0.05$) stillborn rate, with stillborn rate increasing as position in the birth order increased from first to last quartile (1.8 vs. 15.6%).

Survival to weaning

Experiment 1

Piglet birthweight, total born, and colostrum intake were associated ($P < 0.001$) with piglet survival to weaning (Table 5). The lowest birthweight quartile (<1,190 g) had the lowest ($P < 0.05$) percentage of pigs surviving to weaning (59.5%) compared to the other three quartiles. In addition, the heaviest birth weight quartile (> 1,670 g) had greater ($P < 0.05$) percentage of pigs weaned than pigs categorized in the lower three quartiles. Pigs categorized in the lowest two quartiles for total born (<13 and 13 to 14 pigs) had an increased ($P < 0.05$) percentage of pigs weaned compared to the highest two quartiles (15 to 16 and >16 pigs). Pigs categorized in the lowest quartile for colostrum intake (< 337 g) had decreased ($P > 0.05$) percentage of pigs weaned compared to pigs that had consumed more than 337 g of colostrum.

Experiment 2

Multivariate analysis indicated average piglet birth weight, birth order ranking, total born, pig to teat ratio and colostrum intake were associated ($P < 0.01$) with piglet survival to weaning

(Table 6). Each increase in average pig birth weight quartile from lowest to highest improved ($P < 0.05$) the percentage of born alive pigs that were weaned from 62.2% in the lowest quartile (< 1,100 g) to 79.2% in the highest quartile (>1,400 g). Pigs categorized as born in the last quarter of the birth order had decreased ($P > 0.05$) survival to weaning compared to pigs born in the first 3 quarters of the birth order. Each increase in total born quartile from lowest to highest reduced ($P < 0.05$) the percentage of born alive pigs that were weaned from 80.5 in the lowest quartile (< 14 pig) to 60% (>18 pigs). Pigs categorized in the lowest quartile for pig to teat ratio (>0.81) had an increased percentage of pigs survive to weaning compared to pigs in the remaining 3 quartiles. Pigs in the middle two quartiles for pig to teat ratio (0.81 to 1.0, and 1.0 to 1.13) had increased ($P > 0.05$) percentage of pigs survive to weaning compared to pigs in the last quartile (>1.13). Pigs categorized in the lowest quartile of colostrum intake (<302 g) had decreased ($P < 0.05$) percentage survive to weaning compared pigs categorized in the higher 3 quartiles. Lower colostrum intake was associated with an increased pig to teat ratio (Figure 1; $P < 0.001$).

DISCUSSION

The overall stillborn rate in the current two experiments was similar to values reported by other studies with similar number of total born pigs (Rootwelt et al., 2012; Langendijk et al., 2018). The differences in parity distribution between the two herds in the present study may help to explain some of the differences observed in other traits associated with stillborn rate. The present study observed that parity was only associated with increased stillborn rate in Exp. 2, which had an older average parity compared to Exp. 1. It has been well documented that older sows (parity 3 and greater) have an increased stillborn rate, which may be related to poor muscle tone (Vanderhaeghe et al., 2010; Bhattarai et al., 2018). In contrast, first parity sows have also shown evidence for increased stillborn rate, which may be due to a narrower pelvic circumference compared to second parity and older sows (Cowart, 2007); however, this was not observed in the populations of the present study.

Within both herds, sows with lighter average piglet birth weights had a higher stillborn rate, which is potentially a factor of increased total born; however, literature regarding average piglet birthweight and its association with stillborn rate is conflicting. Rootwelt et al. (2012) and Langendijk and Plush (2019) observed no difference in mean piglet birthweight between live born or stillborn pigs. In contrast, several studies have identified light weight pigs to be associated with a higher chance of being stillborn (Herpin et al., 1996; Langendijk et al., 2018; Langendijk and Plush, 2019; Udomchanya et al., 2019). One explanation for the increased stillbirth percentage in light weight pigs is that small pigs are often associated with increased asphyxia as evidenced by increased blood lactate and lower blood pH at birth (Alonso-Spilsbury et al., 2005).

The present study identified heavier litter weights were associated with stillborn rate. To our knowledge, no previous study has evaluated entire litter weight at birth and its association with stillborn rate. The increased stillborn rate associated with heavier litter weights in the current study may be a factor of increased litter size, whereby mean birth weight decreases as litter size increases (Wolf et al., 2008), but total litter birth weight increases. As evidenced above, lighter mean piglet birth weight is associated with increased stillborn rate. Additionally, it has been well established that increased total born is associated with increased stillborn rate (van Dijk et al., 2005; Oliviero et al., 2010; Kirkden et al., 2013; Udomchanya et al., 2019) and our analysis on the piglet level would also support these findings. Thus, the higher observed stillborn rate in the present study as litter weight increased is likely a combination of increased number of total born pigs with lighter mean birth weights. Further, a second model was used for analysis that did not include litter weight due to confounding of litter weight and litter size variables. This model demonstrated that the only change in variables associated with stillborn rate was the addition of sow BW on d 113 of gestation. Litter size could not be used in the model due to being the denominator in the logistic model, therefore it could not be identified as a variable associated with stillborn rate. Because litter size is associated greatly with stillborn rate, by removing litter weight from the model, sow BW was the next variable that shares a relationship with litter size. The explanation for increased stillborn rate as sow BW on d 113 increases could be a factor of increased weight of fetus, placental membranes and fluids with additional total born (Smit et al., 2015).

An increase in farrowing duration was associated with a higher stillborn rate in Exp. 1, which is similar to previous data (Oliviero et al., 2010; Vanderhaeghe et al., 2010; Udomchanya et al., 2019). In contrast, farrowing duration in Exp. 2 was not associated with stillborn rate. This may be due to the difference in the mean farrowing duration between populations (251 vs. 222 min, Exp.1 and Exp. 2, respectively), where the shorter mean farrowing duration in Exp. 2 did not create a scenario supporting increased stillborn rate. In support of this, Vanderhaeghe et al. (2010) indicated that the probability of stillborn pigs was increased in sows farrowing for longer than 240 minutes, in a herd with similar litter size as Exp. 2. Therefore, the impact of farrowing duration on stillborn rate may only be relevant when the sow herd mean farrowing duration exceeds 4 hours.

Previously, over-conditioned sows (>17 mm backfat) have been associated with a longer farrowing duration (Zaleski and Hacker, 1993; Oliviero et al., 2010), and increased body weight gain in late gestation associated with increased stillborn rate (Goncalves et al., 2016). It is hypothesized that over-conditioned females have excess adipose tissue surrounding the birth canal or contributes to a delayed decline in progesterone (Oliviero et al., 2010). In Exp. 1, there was no evidence for sow backfat to influence stillborn rate (mean = 19 ± 3.9) at d 113 of gestation. In contrast, data from Exp. 2 demonstrated thin sows (less than 14 mm backfat) were associated with an increased stillborn rate compared to sows with backfat greater than 14 mm at farrowing. Similarly, two previous studies have observed that sows with backfat less than 12.5 mm at d 109 of gestation (Thongkhuy et al., 2020) or less than 16 mm at farrowing (Vanderhaeghe et al., 2010) had increased risk of stillborn pigs compared to sows with more backfat. One explanation for the increase in stillborn rate with decreasing backfat in Exp. 2 may be attributed to the older average parity herd having a naturally higher stillborn rate, which may have confounded the effect of a sow being both thin and old increasing stillborn rate. Nonetheless, Thongkhuy et al. (2020) observed older parity sows categorized as thin (<12.5 mm backfat) had increased stillborn rate compared to younger parity sows of the same body condition. Furthermore, as parturition progresses, Le Cozler et al. (1999) observed blood glucose concentrations rise which may indicate sows are mobilizing glycogen stores to aid in the completion of parturition when circulating blood glucose has been depleted. Without ample lipid reserves, it may become difficult to meet the energy demands at the end of parturition which could increase the stillborn rate. Although no blood measurements were collected in the present study, the understanding of blood parameters may help to explain the physiology behind the response observed. Care must be taken to not over interpret the current data as the average body condition between the two populations were significantly different. These results suggest that association between sow backfat and stillborn rate may be curvilinear and reiterate the importance of managing sow body condition to avoid too thin or excess body fat in sows entering the farrowing house to minimize risk of stillborn pigs.

Feyera et al. (2018) observed that as time from when a meal was last offered prior to farrowing increased, so did farrowing duration. In Exp. 2, this variable was included in the multivariate analysis but was not found to be associated with stillborn rate or survival to weaning. This may be due to sows in the present study having a shorter average farrowing duration (3.7 vs. 5.8 h) compared to Feyera et al. (2018), and thus not experiencing extreme fatigue during parturition. As litter size continues to increase in U.S. herds, meal timing prior to farrowing may need to be re-evaluated for its association with stillborn rate.

Piglets born later in the birth order have an increased risk of being stillborn (Herpin et al., 1996; Alonso-Spilsbury et al., 2005; Rootwelt et al., 2012). The mechanism for increased stillbirths associated with longer sow farrowing duration and pigs born later in the birth order is largely believed to be due to fetal asphyxia. Farrowing duration can be explained on the sow level, while birth order explains effects observed on the piglet level. Herpin et al. (1996) concluded that pigs born later in the birth order have increased blood lactate and partial pressure of carbon dioxide, and decreased blood pH, which have been documented as signs of asphyxia (Randall, 1972). These physiological changes occurring intrapartum can be attributed to interruption of the oxygen flow through the umbilical cord due to repeated contractions, or even rupturing of the umbilical cord prior to expulsion (Alonso-Spilsbury et al., 2005). Therefore, an increase in farrowing duration naturally increases the risk of all piglets but is exponentially increased with pigs born later in the birth order who experience repeated uterine contractions.

The intrauterine stress often associated with pigs born later in the birth order can reduce the survival of pigs in the extrauterine environment (Zaleski and Hacker, 1993). Pigs are known to be more susceptible to brain damage caused by rupture of the umbilical cord within 5 minutes of delivery (Alonso-Spilsbury et al., 2005). As evidenced in Exp. 2 of the present study, a reduced percentage of pigs were weaned as pigs were born later in the birth order, with this change statistically higher in the last quarter of the litter. This suggests that extra attention needs to be placed on sows near the end of parturition and the liveborn piglets in the last 25% of the litter, as this has implications on survival of pigs at birth and through weaning.

Farrowing assistance through obstetrical intervention of piglets is a common practice to aid in sows experiencing dystocia (Kirkden et al., 2013). While stillborn rates are known to be higher in sows that have received farrowing assistance compared to sows farrowing naturally (Vanderhaeghe et al., 2010), if that same sow had not received farrowing assistance her actual number of stillborn pigs likely would increase. In the present study farrowing assistance was given if the birth interval exceeded 30 to 45 min. While this may have artificially reduced the natural farrowing duration, a greater number of the pigs born that received farrowing assistance were stillborn compared to born alive. This indicates that dystocia was already occurring in the sow; however, it is unknown whether the stillborn pig is the cause of dystocia or the sow's fatigue and lack of uterine contractions caused the stillborn pig (Langendijk and Plush, 2019).

Pig to functional teat ratio was associated with survivability to weaning, where having the same as or fewer number of pigs than functional teats on the sow resulted in improved number of pigs weaned. This is likely due to a decrease in colostrum available per pig, as litter size has not been shown to impact colostrum yield (Devillers et al., 2011; Decaluwé et al., 2014). It is well established that increased colostrum intake is associated with decreased pre-weaning mortality (Devillers et al., 2011; Kirkden et al., 2013). Previous data would suggest that a pig needs to consume a minimum of 200 g of colostrum to survive to weaning (Devillers et al., 2011; Quesnel et al., 2012), whereas our data would suggest that consuming less than 307 g colostrum resulted in almost 50% mortality to weaning. The differences in required colostrum for survival could be explained in part by differences in the equation used to calculate colostrum intake. Previous studies used an equation developed by Devillers et al. (2004), which underestimates colostrum intake by 30% compared to a recently developed equation (Theil et al., 2014) used in the current studies.

Conclusion

The interrelated physical and environmental traits of both sow and piglets (intrauterine and extrauterine) represent a large challenge to identify characteristics that can be influenced in order to improve piglet survivability. Often times, effects of these traits are unable to be completely separated from each other due to biology, therefore making it difficult to identify one key area to focus on. Rather, there are several areas contributed from the sow (litter size, sow body composition, farrowing duration, parity) and from the piglet (birth weight, birth order, colostrum intake) that may have an influence on each other for improved piglet survival. By understanding the magnitude each trait can have towards piglet survival, management strategies in the peripartum to achieve ideal sow body condition, identifying older parity sows needing farrowing assistance, and placing emphasis on pigs born later in the birth order or light weight will lead to increased survival of piglets to weaning. In addition, research strategies to maintain a short farrowing duration (< 4 h) as litter sizes continue to increase will be essential to reduce stillborn rate related to hypoxia.

LITERATURE CITED

Alonso-Spilsbury, M., D. Mota-Rojas, D. Villanueva-Garcia, J. Martinez-Burnes, H. Orozco, R. Ramirez-Necoechea, A. L. Mayagoitia, and M. E. Trujillo. 2005. Perinatal asphyxia pathophysiology in pig and human: A review. Anim. Repro. Sci. 90:1-30. doi: 10.1016/j.anireprosci.2005.01.007

Bhattarai, S., T. Framstad, and J. P. Nielsen. 2018. Stillbirths in relation to sow hematological parameters at farrowing- A cohort study. J. Swine Health Prod. 26:215-222.

Cowart, R. P. 2007. Parturition and dystocia in swine. In: R. S. Youngquist and W. R. Threlfall, editors, Current theory in large animal theriogenology. Saunders, St. Louis, MI.

Decaluwé, R., D. Maes, B. Wuyts, A. Cools, S. Piepers, and G. P. J. Janssens. 2014. Piglets′ colostrum intake associates with daily weight gain and survival until weaning. Livest. Sci. 162:185-192. doi: 10.1016/j.livsci.2014.01.024

Devillers, N., J. Le Dividich, and A. Prunier. 2011. Influence of colostrum intake on piglet survival and immunity. Anim. 5:1605-1612. doi: 10.1017/s175173111100067x

Devillers, N., J. van Milgen, A. Prunier, and J. Le Dividich. 2004. Estimation of colostrum intake in the neonatal pig. Anim. Sci. 78:305-313. doi: 10.1017/S1357729800054096

Feyera, T., T. F. Pedersen, U. Krogh, L. Foldager, and P. K. Theil. 2018. Impact of sow energy status during farrowing on farrowing kinetics, frequency of stillborn piglets, and farrowing assistance. J. Anim. Sci. 96:2320-2331. doi: 10.1093/jas/sky141

Goncalves, M. A. D., K. M. Gourley, S. S. Dritz, M. D. Tokach, N. M. Bello, J. M. DeRouchey, J. C. Woodworth, and R. D. Goodband. 2016. Effects of amino acids and energy intake during late gestation of high-performing gilts and sows on litter and reproductive performance under commercial conditions. J. Anim. Sci. 94:1993-2003. doi: 10.2527/jas.2015-0087

Gourley, K. M., A. J. Swanson, J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. C. Woodworth. 2020a. Effects of increased lysine and energy feeding duration prior to parturition on sow and litter performance, piglet survival, and colostrum quality. J. Anim. Sci. doi: 10.1093/jas/skaa105

Gourley, K. M., A. J. Swanson, R. Q. Royall, J. C. Woodworth, J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, K. J. Milnes, and C. W. Hastad. 2020b. Effects of timing and amount of feed prior to farrowing on sow and litter performance under commercial conditions. J. Anim. Sci. 98. (Abstr.)

Herpin, P., J. Le Dividich, J. C. Hulin, M. Fillaut, F. De Marco, and R. Bertin. 1996. Effects of the level of asphyxia during delivery on vability at birth and early postnatal vitality of newborn pigs. J. Anim. Sci. 74:2067-2075. doi: 10.2527/1996.7492067x

Kirkden, R. D., D. M. Broom, and I. L. Andersen. 2013. Piglet mortality: The impact of induction of farrowing using prostaglandins and oxytocin. Anim. Repro. Sci. 138:14-24.

Langendijk, P., M. Fleuren, H. van Hees, and T. van Kempen. 2018. The course of parturition affects piglet condition at birth and survival and growth through the nursery phase. Animals. 8:60. doi: 10.3390/ani8050060

Langendijk, P., and K. Plush. 2019. Parturition and its relationship with stillbirths and asphyxiated piglets. Animals. 9:885. doi: 10.3390/ani9110885

Le Cozler, Y., V. Beaumal, M. Neil, C. David, and J. Y. Dourmad. 1999. Changes in the concentrations of glucose, non-esterifed fatty acids, urea, insulin, cortisol and some mineral elements in the plasma of the primiparous sow before, during and after induced parturition. Reprod. Nutr. Dev. 39:161-169. doi: 10.1051/rnd:19990201

Nuntapaitoon, M., R. Muns, and P. Tummaruk. 2018. Newborn traits associated with pre-weaning growth and survival in piglets. Asia-Aust. J. Anim. Sci. 31:237-244. doi: 10.5713/ajas.16.0962

Oliviero, C., M. Heinonen, A. Valros, and O. Peltoniemi. 2010. Environmental and sow-related factors affecting the duration of farrowing. Anim. Repro. Sci. 119:85-91. doi: 10.1016/j.anireprosci.2009.12.009

Panzardi, A., M. L. Bernardi, A. P. Mellagi, T. Bierhals, F. P. Bortolozzo, and I. Wentz. 2013. Newborn piglet traits associated with survival and growth performance until weaning. Prev. Vet. Med. 110:206-213. doi: 10.1016/j.prevetmed.2012.11.016

Quesnel, H., C. Farmer, and N. Devillers. 2012. Colostrum intake: Influence on piglet performance and factors of variation. Livest. Sci. 146:105-114. doi: 10.1016/j.livsci.2012.03.010

Randall, G. C. B. 1972. Observations on parturition in the sow. II. Factors influencing stillbirth and perinatal mortality. Vet. Rec. 90:183-186. doi: 10.1136/vr.90.7.183

Rootwelt, V., O. Resen, W. Fastad, and T. Framstad. 2012. Associations between intrapartum death and piglet, placental, and umbilical characteristics. J. Anim. Sci. 90:4289-4296. doi: 10.2527/jas2012-5238

Smit, M. N., J. D. Spencer, J. L. Patterson, M. K. Dyck, W. T. Dixon, and G. R. Foxcroft. 2015. Effects of dietary enrichment with a marine oil-based n-3 LCPUFA supplement in sows with predicted birth weight phenotypes on birth litter quality and growth performance to weaning. Animal 9:471-480. doi: 10.1017/s1751731114002390

Stalder, K. J. 2018. Pork industry productivity analysis, National Pork Board, Des Moines, IA.

Theil, P. K. 2015. Transition feeding of sows. In: C. Farmer, editor, The gestating and lactating sow. Wageningen Academic Publishers, The Netherlands. p. 147-167.

Theil, P. K., C. Flummer, W. L. Hurley, N. B. Kristensen, R. L. Labouriau, and M. T. Sorensen. 2014. Mechanistic model to predict colostrum intake based on deuterium oxide dilution technique data and impact of gestation and prefarrowing diets on piglet intake and sow yield of colostrum. J. Anim. Sci. 92:5507-5519. doi: 10.2527/jas2014-7841

Thongkhuy, S., S. H. B. Chuaychu, P. Burarnrak, P. Ruangjoy, P. Juthamanee, M. Nuntapaitoon, and P. Tummaruk. 2020. Effect of backfat thickness during late gestation on farrowing duration, piglet birth weight, colostrum yield, milk yield and reproductive performance of sows. Livest. Sci. 234doi: 10.1016/j.livsci.2020.103983

Udomchanya, J., A. Suwannutsiri, K. Sripantabut, P. Pruchayakul, P. Juthamanee, M. Nuntapaitoon, and P. Tummaruk. 2019. Association between the incidence of stillbirths and expulsion interval, piglet birth weight, litter size and carbetocin administration in hyper-prolific sows. Livest. Sci. 227:128-134. doi: 10.1016/j.livsci.2019.07.013

van Dijk, A. J., B. van Rens, T. van der Lende, and M. A. M. Taverne. 2005. Factors affecting duration of the expulsive stage of parturition and piglet birth intervals in sows with uncomplicated, spontaneous farrowings. Therio. 64:1573-1590. doi: 10.1016/j.theriogenology.2005.03.017

Vanderhaeghe, C., J. Dewulf, S. De Vliegher, G. A. Papadopoulos, A. de Kruif, and D. Maes. 2010. Longitudinal field study to assess sow level risk factors associated with stillborn piglets. Anim. Reprod. Sci. 120:78-83. doi: 10.1016/j.anireprosci.2010.02.010

Wolf, J., E. Žáková, and E. Groeneveld. 2008. Within-litter variation of birth weight in hyperprolific Czech Large White sows and its relation to litter size traits, stillborn piglets and losses until weaning. Livest. Sci. 115:195-205. doi: 10.1016/j.livsci.2007.07.009

Zaleski, H. M., and R. R. Hacker. 1993. Variables relatated to the progress of parturition and probability of stillbith in swine Can. Vet. J. 34:109-113.

Table 4-1 Population statistics

	Exp. 1[1]		Exp. 2[2]	
Characteristic	Mean (± SD)	Min–Max	Mean (± SD)	Min–Max
Sow				
Parity, n	1.7 (1.6)	0–6	3.9 (1.7)	0–8
Gestation length, d	115.8 (0.8)	113–119	115.5 (1.3)	113–119
Backfat at farrow, mm	19.0 (3.9)	8.0–31.0	13.8 (3.8)	7.0–30.0
Farrowing duration, min	251 (126)	33–739	228 (100)	52–749
Total born, n	14.8 (3.1)	7–22	15.9 (3.6)	6–26
Born alive, %	93.5 (8.1)	50–100	93.4 (7.7)	57.9–100
Stillborn, %	6.5 (8.1)	0–50	6.6 (7.7)	0–42.1
Piglet				
Piglet birth weight, g	1,410 (213)	310–2,630	1,230 (220)	230–2,290
Litter birth weight, kg	21.2 (4.2)	8.6–34.3	19.9 (4.1)	8.3–31.0

[1] A total of 473 sows (Large White × Landrace; parity 1.7 ± 1.6) that gave birth to 6,939 pigs (6,458 live-born and 481 stillborn) were used in analysis.

[2] A total of 728 sows (Fast Large White × PIC Landrace; parity 3.9 ± 1.7) that gave birth to 11,575 pigs (10,758 live-born and 817 stillborn) were used in analysis

Table 4-2 Multivariate logistic regression analysis equations for sow characteristics associated with stillborn rate

Exp. 1[1]		
Response	Equation	BIC[3]
Stillborn rate[4], %	= -3.07 + (0.073 × litter weight (kg)) – (0.001 × piglet weight (g)) + (0.0016 × farrowing duration (min))	1128
Stillborn rate[5], %	= -3.51 + (0.002 × sow BW d 113 (kg)) – (0.0006 × piglet weight (g)) + (0.0017 × farrowing duration (min))	1145
Exp. 2[2]		
Response	Equation	BIC[3]
Stillborn rate[4], %	= -3.648 + (0.068 × litter weight (kg)) – (0.001 × piglet weight (g)) - (0.049 × sow backfat d 113 (mm)) + (0.404 × farrowing assistance (0 or 1[6]) + (0.137 × parity)	1769
Stillborn rate[5], %	= -3.332 + (0.008 × sow BW d 113 (kg)) - (0.652 × piglet weight (g)) - (0.081 × sow backfat d 113 (mm)) + (0.282 × farrowing assistance (0 or 1[6]) + (0.093 × parity)	1793

[1] A total of 473 sows (Large White × Landrace; parity 1.7 ± 1.6) that gave birth to 6,939 pigs (6,458 live-born and 481 stillborn) were used in analysis.

[2] A total of 728 sows (Fast Large White × PIC Landrace; parity 3.9 ± 1.7) that gave birth to 11,575 pigs (10,758 live-born and 817 stillborn) were used in analysis 0 for no farrowing assistance, 1 for at least one pig assisted.

[3] Bayesian information criterion.

[4] Analysis utilizing litter weight as a variable in the model.

[5] Analysis removing litter weight as a variable in the model.

[6] Farrowing assistance reported as no pigs assisted (0), or at least one pig assisted (1) per sow.

Table 4-3 Quartiles for sow and piglet characteristics associated with stillborn rate, Exp. 1

Variable	Quartiles					
Litter weight[1], kg	<18.1	18.1-21.2	21.3-23.9	>24	SEM	*P*-value
Stillborn, %	4.9^{c}	6.0^{bc}	7.1^{ab}	8.6^{a}	0.55	< 0.001
Mean pig birth weight[1], g	<1,300	1,300-1,420	1,430-1,570	>1,580	SEM	*P*-value
Stillborn, %	8.8^{a}	6.7^{ab}	5.7^{b}	5.9^{b}	0.53	0.011
Farrowing duration[1], min	<162	162-224	225-307	>308	SEM	*P*-value
Stillborn, %	4.5^{c}	5.9^{bc}	6.8^{b}	9.3^{a}	0.60	< 0.001
Sow BW d 113[1], kg	<236	236-266	267-292	>292	SEM	*P*-value
Stillborn, %	5.7^{b}	5.9^{b}	7.2^{ab}	8.4^{a}	0.64	0.036
Total born[2]	<13	13-14	15-16	>16	SEM	*P*-value
Stillborn, %	4.7^{c}	5.7^{bc}	7.1^{b}	10.5^{a}	0.51	< 0.001
Birth order ranking[2]	<25	25-50	50-75	>75	SEM	*P*-value
Stillborn, %	1.6^{d}	3.2^{c}	6.4^{b}	18.7^{a}	0.50	< 0.001

[1] A total of 473 sows were categorized into quartiles within each response variable, with each quartile representing approximately 25% of sows in the study population.

[2] A total of 6,939 piglets (6,458 live-born and 481 stillborn) were categorized into quartiles within each response variable, with each quartile representing approximately 25% of sows or piglets in the study population.

$^{a\text{-}d}$Means within a row not sharing a common superscript differ, $P < 0.05$.

Table 4-4 Quartiles for sow and piglet characteristics associated with stillborn rate, Exp. 2

Variable	Quartiles					
Litter birth weight[1], kg	<16.9	16.9-19.7	19.8-22.4	>22.4	SEM	*P*-value
Stillborn, %	5.9^{b}	6.9^{ab}	6.4^{ab}	8.1^{a}	0.51	0.050
Mean pig birth weight[1], g	<1,100	1,100-1,240	1,250-1,390	>1,400	SEM	*P*-value
Stillborn, %	8.2^{a}	7.5^{ab}	6.4^{bc}	5.4^{c}	0.50	0.005
Sow back fat d 113[1], mm	<11	11-13	14-16	>16	SEM	*P*-value
Stillborn, %	8.7^{a}	7.2^{ab}	6.8^{b}	5.6^{b}	0.57	0.004
Sow BW d 113[2], kg	<244	244-261	262-279	>279	SEM	*P*-value
Stillborn, %	5.4^{b}	6.9^{ab}	7.4^{a}	7.8^{a}	0.50	0.027
Parity[1]	<3	3	4	>4	SEM	*P*-value
Stillborn, %	4.3^{c}	5.5^{bc}	6.8^{b}	8.6^{a}	0.55	< 0.001
Sow farrowing assistance[1,2]	No	Yes			SEM	*P*-value
Stillborn, %	5.0	7.6			0.41	< 0.001
Total born[3], n	<14	14-16	17-18	>18	SEM	*P*-value
Stillborn, %	4.7^{c}	6.1^{bc}	6.9^{b}	10.1^{a}	0.50	< 0.001
Birth order ranking[3], %	<25	25-50	50-75	>75	SEM	*P*-value
Stillborn, %	1.8^{d}	3.7^{c}	8.0^{b}	15.6^{a}	0.46	< 0.001

[1] A total of 728 sows were categorized into quartiles within each response variable, with each quartile representing approximately 25% of sows in the study population.

[2] Sow farrowing assistance was recorded for each sow. Yes represents at least one pig was pulled from the sow, no represents that no piglets were assisted out. Means represent the stillborn rate within each category.

[3] A total of 11,575 piglets (10,758 live-born and 817 stillborn) were categorized into quartiles within each response variable, with each quartile representing approximately 25% of piglets in the study population.

$^{a-d}$Means within a row not sharing a common superscript differ, *P* < 0.05.

Table 4-5 Quartiles for sow and piglet characteristics associated with survival to weaning, Exp 1[1,2]

Variable	Quartiles					
Birth weight, g	<1,190	1,190-1,430	1,440-1,660	>1,670	SEM	*P*- value
Weaned, %	59.5^{a}	82.1^{b}	84.4^{b}	88.6^{c}	1.20	< 0.001
Total born, n	<13	13-15	16-17	>17	SEM	*P*- value
Weaned, %	87.1^{a}	83.7^{a}	78.3^{b}	69.5^{c}	1.02	< 0.001
Colostrum intake, g	<337	337-442	442-550	>550	SEM	*P*- value
Weaned, %	73.7^{c}	91.8^{b}	94.9^{a}	95.9^{a}	1.15	< 0.001

[1] Percentage weaned is calculated as weaned count divided by total born.

[2] A total of 6,939 piglets (6,458 live-born and 481 stillborn) were categorized into quartiles within each response variable, with each quartile representing approximately 25% of sows or piglets in the study population.

[a-c] Means within a row not sharing a common superscript differ $P < 0.05$.

Table 4-6 Quartiles for piglet characteristics associated with survival to weaning, Exp. 2[1,2]

Variable	Quartiles					
Pig birth weight, g	<1,100	1,100-1,240	1,250-1,390	>1,400	SEM	*P*-value
Weaned %	62.2^{d}	68.6^{c}	72.5^{b}	79.2^{a}	0.89	0.005
Birth order ranking, %	<25	25-50	50-75	>75	SEM	*P*-value
Weaned, %	71.4^{a}	72.2^{a}	70.4^{a}	66.1^{b}	0.93	< 0.001
Total born, n	<14	14-16	17-18	>18	SEM	*P*-value
Weaned, %	80.5^{a}	74.6^{b}	68.2^{c}	60.0^{d}	0.90	<0.001
Pig:Teat[3]	<0.81	0.81-1.00	1.00-1.13	>1.13	SEM	*P*-value
Weaned, %	76.8^{a}	72.6^{b}	69.6^{b}	63.3^{c}	0.90	0.001
Colostrum intake, g	<302	302-408	408-509	>509	SEM	*P*-value
Weaned, %	52.1^{d}	83.3^{c}	91.6^{b}	93.7^{a}	0.93	< 0.001

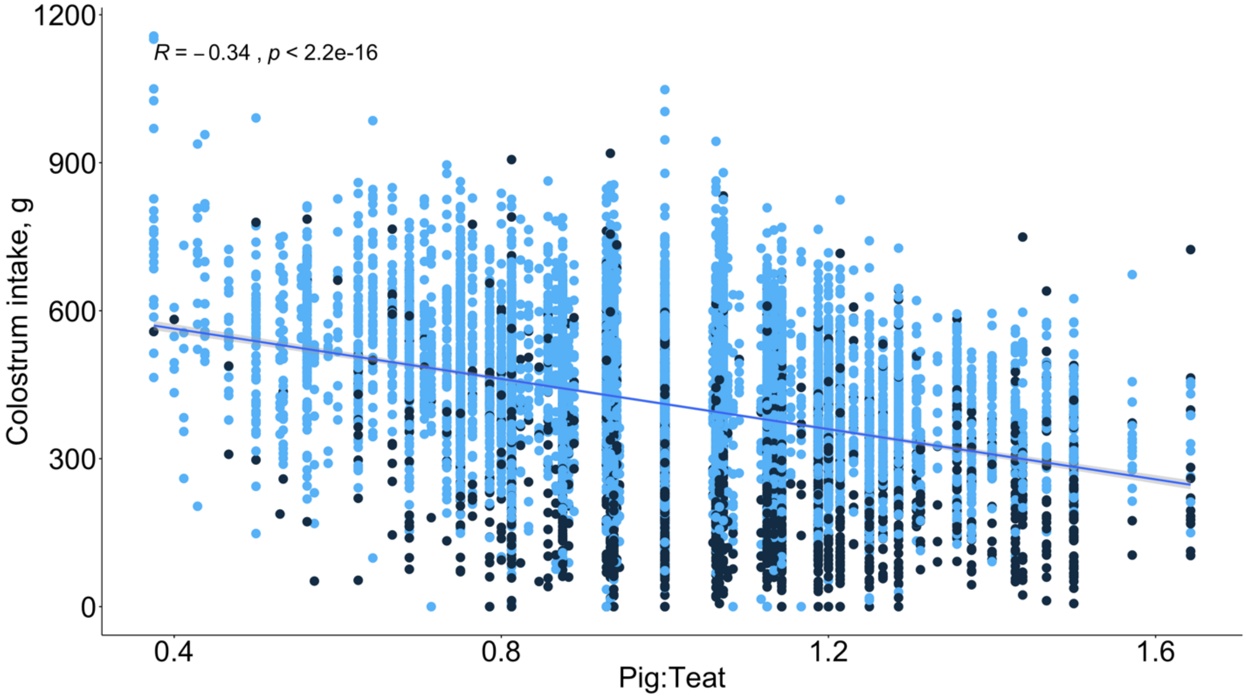
[1] Percentage weaned is calculated as weaned count divided by born alive.

[2] A total of 11,575 piglets (10,758 live-born and 817 stillborn) were categorized into quartiles within each response variable, with each quartile representing approximately 25% of piglets in the study population.

[3] Pig to teat ratio is the number of born alive pigs divided by functional teats per sow.

[a-d] Means within a row not sharing a common superscript differ $P < 0.05$.

Figure 4-1 Correlation between pig to teat ratio and colostrum intake, in relation to survival at weaning in Exp 2.[1]



[1] A total of 10,758 live-born pigs are represented. Colostrum intake was calculated as described by Theil et al. (2014). Pig to teat ratio is the number of born alive piglets divided by number of functional teats per sow. Light dots represent pigs that were alive at weaning. Dark dots represent pigs that were a mortality before weaning.

Chapter 5 - Associations between piglet umbilical blood hematological criteria, birth order, birth interval, colostrum intake and piglet survival

ABSTRACT

A total of 656 pigs (623 live-born and 33 stillborn) from 43 sows were used to evaluate hematological criteria at birth and their association with piglet survival. At birth of each piglet, birth time and order within the litter, weight, umbilical cord status (intact or ruptured) and wether the pig was live-born or stillborn were recorded. A 200µL sample of blood from the umbilical cord was collected and immediately analyzed for concentrations of glucose, oxygen partial pressure (**pO_2**), carbon dioxide partial pressure (**pCO_2**), pH, base excess (**BE**), bicarbonate (**HCO_3**), saturated oxygen (**sO_2**), total carbon dioxide (**TCO_2**), sodium, potassium, ionized calcium (**iCa**), hematocrit (**Hct**), and hemoglobin (**Hb**) on a hand held iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ). Piglets were categorized into quartiles based on birth order and cumulative birth interval (**CumBI**). Live-born pigs had higher ($P < 0.01$) umbilical cord blood pH, HCO_3, BE, sO_2, TCO_2, and birth weight compared to stillborn pigs, but lower ($P < 0.01$) pCO_2, K, iCa, and glucose compared to stillborn pigs. Pigs with intact umbilical cords at birth were associated with higher ($P < 0.01$) blood pH, HCO_3, BE, and TCO_2 compared to piglets born with a ruptured umbilical cord. Pigs with intact umbilical cords were associated with lower ($P < 0.01$) Hct and Hb concentrations and born earlier ($P < 0.01$) in the birth order compared to pigs born with a ruptured umbilical cord. Pigs that did not survive to weaning had lower ($P < 0.01$) umbilical cord blood pH, HCO_3, BE, sO_2, TCO_2, Na, glucose, and birth weight, and 24 h weight compared to pigs alive at weaning. Pigs born in the first quartile for CumBI had higher ($P < 0.05$) pH compared to pigs in the other three quartiles. Umbilical cord blood HCO_3, BE, and TCO_2 decreased ($P < 0.05$) with each change in CumBI quartile from first to last. Blood glucose was lowest ($P < 0.05$) in pigs born before 44 min and highest in pigs born after 164 min. Umbilical cord blood pH, HCO_3, BE, TCO_2, Na, glucose, Hct, and Hb were positively associated ($P < 0.001$) with colostrum intake, indicating increased blood values resulted in higher colostrum intake. Although a pig may be live-born, their survival to 24 h and to weaning is reduced when blood pH, HCO_3, BE, and sO_2 are lower reiterating the importance of management practices that can reduce the birth interval between pigs and the number of pigs experiencing moderate to severe hypoxia.

INTRODUCTION

Fetal hypoxia during parturition is a common event in swine because they are a litter bearing species. Hypoxia is typically considered a cause of stillborn piglets and reduced piglet vitality in the first few hours of life (Alonso-Spilsbury et al., 2005). Many physiological traits with both the sow and piglet have been associated with an increased risk of hypoxia, such as increased farrowing duration, larger litter size, successive uterine contractions, and born later in the birth order (Randall, 1972; Alonso-Spilsbury et al., 2005). The physiological changes occurring in pigs that suffer from fetal hypoxia often include indications of acidosis such as an increase in blood lactate and a concurrent decrease in blood pH.

As litter size continues to increase in modern high-prolific sows, a concurrent increase in farrowing duration has also been observed and is associated with increased stillborn rate (van Dijk et al., 2005; Theil, 2015). Quantifying the effect of birth order and length of parturition on hematological criteria in piglets can help to identify piglets that have experienced hypoxia during the parturition process (Langendijk et al., 2018). Furthermore, understanding the magnitude and relationship between acid-base balance in blood at birth on the piglet's ability to consume colostrum and survive in the first 24 h after birth and to weaning can help identify sow management or nutritional strategies that can increase piglet survival. Therefore, the objective of the present study was to identify associations between umbilical cord hematological criteria and piglet birth order, birth interval, colostrum intake, and piglet survival.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This study was conducted on a commercial 3,000-sow farm in southern Minnesota during summer 2019. The facilities were environmentally controlled with mechanical ventilation.

A total of 43 sows (Fast Large White × PIC Landrace) were randomly selected over a 7-week period to be continuously monitored during farrowing. On d 113 of gestation, sows were moved from gestation stalls into farrowing stalls. Each farrowing stall was equipped with a shelf feeder and nipple drinker for the sows, and a heat mat and nipple drinker for the piglets. Sows were continuously monitored during farrowing for accurate recording of all variables and timely collection of umbilical cord blood. All live and dead full-term piglets were included in the study, whereas mummified fetuses were excluded. Farrowing assistance was given to the sow if the birth interval exceeded 30 to 45 minutes between piglets.

A total of 683 pigs (638 live-born and 45 stillborn) from 43 sows were included in the study. As each piglet was born, birth time, birth order, birth weight, and farrowing assistance (assisted or unassisted) were recorded. The umbilical cord was identified as intact or ruptured (visible signs of breakage due to sow contractions or stretching intrauterine) at birth. A 200 μL sample of mixed venous and arterial blood from the proximal end of the umbilical cord was collected into a lithium heparin tube within 1 min of birth of each pig. Whole blood was immediately analyzed for concentrations of glucose, oxygen partial pressure (**pO_2**), carbon dioxide partial pressure (**pCO_2)**, pH, base excess (**BE**), bicarbonate (**HCO_3**), saturated oxygen (**sO_2**), total carbon dioxide (**TCO_2),** sodium, potassium, ionized calcium (**iCa**), hematocrit (**Hct**), and hemoglobin (**Hb**) on a hand held iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

After blood collection, all piglets were weighed, individually identified with an ear tag, dried using a desiccant (Techdry; TechMix, LLC., Stewart, MN) and a paper towel, and placed next to the sow's underline. Cumulative birth interval for each pig born was calculated as the time elapsed from the birth of first pig until birth time of the current pig. Piglets were reweighed at 24 h after birth of the first pig to calculate colostrum intake as described by Theil et al. (2014). All live-born piglets were followed until weaning, with all removals and mortalities weighed and recorded. At weaning (d 21 ± 2), each piglet was weighed to calculate piglet growth rate.

Statistical analysis

Birth order ranking was calculated for each pig as: [(pig birth order-1)/(total born-1)], as described by van Dijk et al. (2006), where the first pig in each litter would have rank 0, and the last pig would have a ranking of 1. Pigs with a higher number in birth order ranking means they were born later in the birth order of that litter. Pigs were then categorized into 4 birth order categories: category 1 ≤ 0.25, $0.25 <$ category 2 ≤ 0.50, $0.50 <$ category 3 ≤ 0.75, category 4 > 0.75. Pigs were also categorized according to their birth interval. Cumulative birth interval

(**CumBI**) categories were selected based on quartiles of the pig population, and were as follows: CumBI ≤ 44 min, 44 < CumBI ≤ 95 min, 95< CumBI ≤ 164, CumBI > 164.

Data were analyzed using generalized linear mixed models, where pig was the experimental unit, birth type (live-born or stillborn) was the fixed effect, with the random effect of sow. Separate linear mixed models were used to evaluate the fixed effects of umbilical cord status (ruptured or intact), farrowing assistance (unassisted or assisted), birth order category, CumBI category, pig status at 24 h (dead or alive), and pig status at weaning (dead or alive). Statistical models were fit using linear models using the Lme function (lmer package of R, version 3.5.2). Residuals of each blood criteria were checked for normal distribution. The blood criteria pCO_2, pO_2, and glucose were not normally distributed therefore they were log transformed for analysis. Multiple mean comparisons were performed with adjustments according to Tukey-Kramer. Univariate linear regression analyses were used for evaluating the association between colostrum intake and umbilical cord hematological criteria or total born. Results were considered significant at $P < 0.05$.

RESULTS

Of the 683 live-born and stillborn pigs, blood samples were unable to be collected from 12 stillborn pigs due to lack of blood in the umbilical cord. In addition, 15 live-born piglets did not produce enough blood to be used in the iStat analyzer and therefore were excluded from analysis. As a result, data were collected from 623 live-born and 33 stillborn piglets (Table 1).

Live-born vs. stillborn

Live-born pigs had higher ($P < 0.01$) umbilical blood pH, HCO_3, BE, sO_2, TCO_2, and birth weight compared to stillborn pigs, whereas stillborn pigs had higher ($P < 0.01$) pCO_2, K, iCa, and glucose compared to live-born pigs (Table 2). There was no evidence for a difference ($P > 0.05$) between live-born or stillborn pigs for pO_2, Hct, or Hb concentrations in umbilical cord blood.

Umbilical cord status

Pigs with intact umbilical cords at birth were associated with higher ($P < 0.01$) pH, HCO_3, BE, and TCO_2 blood concentrations compared to piglets born with a ruptured umbilical cord (Table 3). Piglets with a ruptured umbilical cord were associated with higher ($P < 0.01$) Hct and Hb concentrations and born later ($P < 0.01$) in the birth order compared to pigs born with an intact umbilical cord. There was no evidence for difference ($P > 0.05$) in blood pCO_2, pO_2, sO_2, Na, K, iCa, glucose or birth weight between pigs born with an intact or ruptured umbilical cord. Born alive pigs had a lower percentage of pigs born with ruptured umbilical cords compared to stillborn pigs (17.9 vs. 43.1 %).

Farrowing assistance

Of the 656 pigs, 113 pigs (17.2%) were physically assisted out of the birth canal. Pigs that were unassisted had higher ($P < 0.01$) blood pH, pO_2, HCO_3, BE, sO_2, TCO_2, Na, Hct, and Hb compared to piglets that had been assisted (Table 4). Pigs that were assisted had higher ($P < 0.01$) iCa and glucose concentrations compared to piglets that were unassisted. There was no evidence for difference ($P > 0.05$) in umbilical cord pCO_2, K, or birth weight between pigs that were unassisted compared to assisted at birth.

Survival to 24 h

Of the 623 pigs live-born, 38 (6.1%) were classified as a mortality before 24 h after birth. Pigs that did not survive to 24 h after birth had lower ($P < 0.01$) blood pH, HCO_3, BE, sO_2, TCO_2, glucose concentrations and birth weight compared to piglets that were alive at 24 h. Pigs that survived to 24 h had lower ($P < 0.01$) $p\mathrm{CO}_2$ and iCa compared to pigs that died in the first 24 h of life. There was no evidence for difference ($P > 0.05$) between pigs that survived or died in the first 24 h for $p\mathrm{O}_2$, Na, K, Hct, Hb, or birth order.

Survival to weaning

Of the 623 pigs live-born, 158 (25.3%) were classified as a mortality before weaning (Table 6). Pigs that did not survive to weaning had lower ($P < 0.01$) blood pH, HCO_3, BE, $s\mathrm{O}_2$, TCO_2, Na, glucose, birth weight, and 24 h weight compared to pigs alive at weaning. Pigs that survived to weaning had lower ($P < 0.01$) iCa compared to pigs that died before weaning. There was no evidence for difference between pigs that survived or died before weaning for $p\mathrm{CO}_2$, $p\mathrm{O}_2$, K, Hct, or Hb.

Birth order

As birth order ranking increased from < 0.25 to > 0.75, blood pH decreased ($P < 0.05$) between each category (Table 7). Pigs in the first birth order category had lower ($P < 0.05$) $p\mathrm{CO}_2$ compared to pigs in the higher three categories. Partial oxygen was highest ($P < 0.05$) in pigs born in the third birth order category compared to pigs born in the first two categories with pigs in the last category intermediate. Both HCO_3 and BE were similar ($P > 0.05$) in pigs born in the first two categories but was decreased ($P < 0.05$) in pigs in the third category, and lowest ($P < 0.05$) in pigs in the fourth category. The sO2 was higher ($P < 0.05$) in pigs born in the third category compared to pigs born in the fourth category, with pigs born in the first half of the litter intermediate. Pigs born in birth order categories 1 and 2 had increased TCO_2 ($P < 0.05$) compared to pigs born in categories 3 and 4. Sodium was higher ($P < 0.05$) in pigs born in the first category compared to those born in the last with the others intermediate. Potassium was higher ($P < 0.05$) for pigs born in the second half of farrowing compared to the first. As birth order ranking increased, iCa increased ($P < 0.05$) with the highest ($P < 0.05$) iCa observed in pigs born in the fourth category. Glucose concentration was highest ($P < 0.05$) in pigs born in the third category compared to pigs born in the first category, with pigs born in the second category intermediate. Pigs born in the last category of the litter had the highest ($P < 0.05$) blood glucose concentrations. Hemoglobin and Hct were higher ($P < 0.05$) in pigs born in the last category compared to pigs born in the first or third categories, with pigs born in the second category intermediate. Birth weight was heaviest ($P < 0.05$) in pigs born in the last category compared to pigs born in the first three categories of the litter.

Cumulative birth interval

Pigs born in the first quartile for CumBI (< 44 min) had higher ($P < 0.05$) pH compared to pigs in the other three quartiles (Table 8). Pigs born in the second or third quartile (44 to 95 or 95 to 164 min) had higher ($P < 0.05$) pH compared to pigs in the fourth quartile (>164 min). The HCO_3, BE, and TCO_2 decreased ($P < 0.05$) with each change in CumBI quartile from first to last, with the lowest HCO_3, BE and TCO_2 observed in pigs born after 164 min. Pigs born within 44 min had higher ($P < 0.05$) Na compared to pigs born after 95 min, with pigs born between 44 and 95 min intermediate. Pigs born within 44 min had lower ($P < 0.05$) K than pigs born after 164 min, with those born in the middle two CumBI quartiles intermediate. Pigs born before 95 min had lower ($P < 0.05$) iCa compared to pigs born after 95 min for CumBI. Blood glucose was lowest ($P < 0.05$) in pigs born within 44 min, compared to pigs born in the third CumBI quartile (95 to 165 min), with pigs in the second quartile (44 to 95 min) intermediate. Pigs born after 164 min had the highest ($P < 0.05$) blood glucose concentrations compared to pigs in the first three CumBI quartiles. Pigs born within the first 44 min were lighter ($P < 0.05$) compared to pigs born after 95 min, with pigs born between 44 and 95 min intermediate. There was no evidence ($P >$ 0.05) for CumBI to influence pCO_2, pO_2, sO_2, Hct or Hb.

Colostrum intake associations

Total born was negatively associated ($P < 0.001$) with colostrum intake, as pigs in large litters consumed less colostrum than pigs in small litters (Table 9). Umbilical cord blood pH, HCO_3, BE, TCO_2, Na, glucose, Hct, and Hb were positively associated ($P < 0.001$) with colostrum intake. There was no evidence ($P < 0.001$) for association between pCO_2, pO_2, sO_2, or K and colostrum intake.

DISCUSSION

Mean hematological criteria collected on piglets using the iStat portable analyzer were similar to previous values (Rootwelt et al., 2012; van den Bosch et al., 2019). Litter size of previous studies ranged from 11.7 to 15.9 and average sow parity ranged from 2.0 to 4.2. Sows used in previous studies were Landrace × Yorkshire, Landrace × Large White, or purebred Landrace. While populations varied in the previous studies are spread over several years (van Dijk et al., 2006; Rootwelt et al., 2012; Langendijk et al., 2018; van den Bosch et al., 2019), the range in total born, sow parity, and genetics would be similar to the population of the current study.

Birth status

Intrapartum death resulting in stillborn or mummified fetuses accounts for 9.8% of total born pigs (Stalder, 2018). While mummified fetuses are typically caused from disease, the majority of stillborn pigs occur during the parturition process due to oxygen deprivation (Randall, 1972). Friendship et al. (1990) evaluated cesarean records from 827 sows and observed

2 to 3% of stillborn pigs were unable to be prevented. Several studies have focused on the acid-base balance of piglet blood and identified that pigs which experience asphyxia during parturition are identifiable by decreased blood pH and pO_2, increased lactate, glucose and pCO_2 concentrations (Alonso-Spilsbury et al., 2005; Mota-Rojas et al., 2012; Rootwelt et al., 2012; Langendijk and Plush, 2019). These changes to the acid-base balance are largely due to interruption of oxygen delivery to the fetus during parturition resulting in respiratory acidosis as fetal CO_2 and H_2CO_3 increase, reducing blood pH and shifting towards anaerobic metabolism. This metabolic shift increases lactic acid production further reducing pH, ultimately ending in metabolic acidosis and intrapartum death of the fetus (Alonso-Spilsbury et al., 2005). This cascade of events was observed in our present study as stillborn pigs had increased CO_2 and reduced pH, BE, and sO_2 compared with live-born pigs. Hypoxia can also disrupt cell membranes and decrease ATPase, Na, and K, which is supported by the decreased Na and increased K observed in blood of stillborn pigs (Alonso-Spilsbury et al., 2005). Furthermore, glucose concentrations in blood will increase during times of stress due to the activation of the sympathetic nervous system initiating glycogenolysis. In general, piglet blood glucose at birth is relatively low (< 50 mg/dL) and in fact increased blood glucose measured at birth is not a sign of ability to adapt to extra-uterine life but another indicator of hypoxia during parturition (Herpin et al., 1996).

Signs of asphyxia defined as a decrease in blood acid-base balance are also indicators of postnatal survival (Herpin et al., 1996; Tuchscherer et al., 2000; Mota-Rojas et al., 2005; Langendijk et al., 2018). It has been estimated that 14 to 20% of live-born piglets are asphyxiated at birth (Mota-Rojas et al., 2012; Langendijk and Plush, 2019). Langendijk et. al. (2018), evaluated the degree of lactate concentration at birth, as a measure of asphyxia, and observed a reduction in d 7 survival of piglets as lactate concentration increased from < 3.6 mmol/L to > 6.40 mmol/L. The authors also observed decreased piglet gain during lactation in pigs born with increased lactate concentrations, but this was confounded with birth weight where pigs with high lactate also had the lowest birth weight (Langendijk et al., 2018). Regardless, it is likely a combination of low birth weight and increased duration of asphyxiation during parturition that contribute to pre-weaning mortality. The present study indicated that the population of pigs alive at 24 h and at weaning had improved umbilical cord blood pH, BE, sO_2, and glucose at birth and heavier birth weights compared to pigs recorded as a mortality. These data reiterate the importance of management practices around or during parturition, such as manual assistance to relieve dystocia (Kirkden et al., 2013) to help reduce the number of piglets experiencing extreme asphyxiation. Furthermore, targeted piglet management protocols such as split suckling may improve the survival of piglets that are born asphyxiated.

Colostrum intake

Tuchscherer et al. (2000) identified pigs that survived to d 10 of life were associated with reduced time from birth to first suckle (27 vs. 54 min). Herpin et al. (1996) observed a delayed time to contact the udder in pigs with increased lactate concentration at birth, which is a disadvantage for colostrum consumption. In support of this, Langendijk et al. (2018) observed decreased colostrum intake in piglets that experienced asphyxia during parturition. Our data would concur with these results, as decreases in umbilical cord blood pH, pCO_2 and HCO_3 were associated with decreased colostrum intake. Ultimately, these results support that piglets with a shorter time to contact the udder and increased vigor at birth will have increased colostrum intake and increase survival to weaning (Panzardi et al., 2013; Ferrari et al., 2014).

Umbilical cord morphology

Several studies have documented the morphology of umbilical cord in relation to piglet vitality at birth (Randall, 1972; Herpin et al., 1996; van Dijk et al., 2006). An observed risk of mortality has been found when a ruptured cord is present at birth compared to umbilical cords that are intact (Herpin et al., 1996). A ruptured cord can be caused by increased contractions with oxytocin use, repeated contractions experienced by pigs born later in the birth order, or twisting of the umbilical cord while moving through the birth canal (Mota-Rojas et al., 2005). Langendijk et al. (2018) observed pigs born with ruptured umbilical cords had more signs of asphyxia, as evidenced by lower pH and increased blood lactate concentrations, compared to piglets with intact umbilical cords at birth. In the present study, lower pH and BE were observed in pigs with ruptured umbilical cord indicating signs of hypoxia as a result of reduced blood flow were beginning intrapartum, which supports previous findings that ruptured umbilical cords are a risk factor for intrapartum death or reduced survival during lactation.

Birth order and cumulative birth interval

The continual increase in litter size from genetic selection has concurrently increased farrowing duration, which increases the risk of metabolic acidosis and hypoxia due to extended parturition (Vanderhaeghe et al., 2013; Feyera et al., 2018). As the pig spends longer time in utero during farrowing, the pig is exposed for more contractions which can result in reduced oxygen supply or damage to the umbilical cord (Alonso-Spilsbury et al., 2005; van Dijk et al., 2006). Studies have demonstrated that as pigs are born later in the birth order, pH and BE in umbilical cords were decreased and lactate concentration increased indicating pigs born later were experiencing acidosis and perhaps asphyxia (Herpin et al., 1996; Langendijk et al., 2018).

However, identifying the time during the farrowing process at which asphyxiation starts to increase can be helpful of identifying intervention timing.

van Dijk et al. (2006) categorized CumBI into three classes (first, middle, or last third of farrowing) and observed a decrease in pig blood pH, HCO_3 and BE, and an increase in $p\mathrm{CO}_2$ as pigs were born later after a longer CumBI. In the present study, the CumBI quartiles further quantify the changes in acid-base balance begins as early as 45 min after the onset of parturition, but are exponentially increased in pigs born after 164 min. Furthermore, we identified pigs born later in the birth order also had heavier birth weights. Rootwelt et al. (2012) also documented that a heavier birth weight, placental weight and placental area were observed for pigs born in the last third of the litter. While birth order and birth weight may be confounded, it is interesting to note that heavier pigs are observed near the end of the birth order where the stillborn rate is increased. It could be hypothesized that heavy pigs at the end of the birth order may increase dystocia in sows, resulting in increased stillborn rate or prolonged farrowing duration. In future research it will be important to measure both birth order ranking and the CumBI because while birth order cannot be changed by management practices, the CumBI can be controlled to an extent by farrowing assistance. It may be suggested that if the last-born pig experiences a low CumBI, its chance of survival may be equal to that of its earlier born littermates indicating that time is a larger contributor to acidosis and asphyxia compared to simply birth order.

Summary

In conclusion, the present data is the first to evaluate the association between umbilical cord blood criteria and colostrum intake, and further quantify the magnitude of change in piglet umbilical cord hematological criteria as cumulative birth interval and birth order increases. Our data supports the changes in umbilical cord acid-base balance as an indicator for hypoxia with an increase in cumulative birth interval, especially in pigs experiencing parturition longer than 164 min. Furthermore, the present study validates previous data on changes in umbilical cord blood acid-base balance and glucose between live-born and stillborn pigs, and pigs with ruptured umbilical cords at birth. Although a pig may be live-born, it's survival to 24 h and to weaning is characterized by low blood pH, HCO_3, BE, and sO_2 reiterating the importance of management practices that can reduce the birth interval between pigs and the number of pigs experiencing moderate to severe hypoxia.

LITERATURE CITED

Alonso-Spilsbury, M., D. Mota-Rojas, D. Villanueva-Garcia, J. Martinez-Burnes, H. Orozco, R. Ramirez-Necoechea, A. L. Mayagoitia, and M. E. Trujillo. 2005. Perinatal asphyxia pathophysiology in pig and human: A review. Anim. Repro. Sci. 90:1-30. doi: 10.1016/j.anireprosci.2005.01.007

Ferrari, C. V., P. E. Sbardella, M. L. Bernardi, M. L. Coutinho, I. S. Vaz, I. Wentz, and F. P. Bortolozzo. 2014. Effect of birth weight and colostrum intake on mortality and performance of piglets after cross-fostering in sows of different parities. Prev. Vet. Med. 114:259-266. doi: 10.1016/j.prevetmed.2014.02.013

Feyera, T., T. F. Pedersen, U. Krogh, L. Foldager, and P. K. Theil. 2018. Impact of sow energy status during farrowing on farrowing kinetics, frequency of stillborn piglets, and farrowing assistance. J. Anim. Sci. 96:2320-2331. doi: 10.1093/jas/sky141

Friendship, R. M., K. R. Metzger, N. P. Robinson, and G. S. Doig. 1990. Cesarean section in the sow: A retrospective analysis of litter size and stillbirth rate. Can. Vet. J. 31:697-699.

Herpin, P., J. Le Dividich, J. C. Hulin, M. Fillaut, F. De Marco, and R. Bertin. 1996. Effects of the level of asphyxia during delivery on vability at birth and early postnatal vitality of newborn pigs. J. Anim. Sci. 74:2067-2075. doi: 10.2527/1996.7492067x

Kirkden, R. D., D. M. Broom, and I. L. Andersen. 2013. Piglet mortality: The impact of induction of farrowing using prostaglandins and oxytocin. Anim. Repro. Sci. 138:14-24.

Langendijk, P., M. Fleuren, H. van Hees, and T. van Kempen. 2018. The course of parturition affects piglet condition at birth and survival and growth through the nursery phase. Animals. 8:60. doi: 10.3390/ani8050060

Langendijk, P., and K. Plush. 2019. Parturition and its relationship with stillbirths and asphyxiated piglets. Animals. 9:885. doi: 10.3390/ani9110885

Mota-Rojas, D., J. Martinez-Burnes, M. E. Trujillo, A. Lopez, A. M. Rosales, R. Ramirez, H. Orozco, A. Merino, and M. Alonso-Spilsbury. 2005. Uterine and fetal asphyxia monitoring in parturient sows treated with oxytocin. Anim. Reprod. Sci. 86:131-141. doi: 10.1016/j.anireprosci.2004.06.004

Mota-Rojas, D., J. Martinez-Burnes, D. Villanueva-Garcia, P. Roldan-Santiago, M. E. Trujillo-Ortega, H. Orozco-Gregorio, H. Bonilla-Jaime, and A. Lopez. 2012. Animal welfare in the newborn piglet: a review. Veterinarni Medicina 57:338-349. doi: 10.17221/6262-vetmed

Panzardi, A., M. L. Bernardi, A. P. Mellagi, T. Bierhals, F. P. Bortolozzo, and I. Wentz. 2013. Newborn piglet traits associated with survival and growth performance until weaning. Prev. Vet. Med. 110:206-213. doi: 10.1016/j.prevetmed.2012.11.016

Randall, G. C. B. 1972. Observations on parturition in the sow. II. Factors influencing stillbirth and perinatal mortality. Vet. Rec. 90:183-186. doi: 10.1136/vr.90.7.183

Rootwelt, V., O. Resen, W. Fastad, and T. Framstad. 2012. Associations between intrapartum death and piglet, placental, and umbilical characteristics. J. Anim. Sci. 90:4289-4296. doi: 10.2527/jas2012-5238

Stalder, K. J. 2018. Pork industry productivity analysis, National Pork Board, Des Moines, IA.

Theil, P. K. 2015. Transition feeding of sows. In: C. Farmer, editor, The gestating and lactating sow. Wageningen Academic Publishers, The Netherlands. p. 147-167.

Theil, P. K., C. Flummer, W. L. Hurley, N. B. Kristensen, R. L. Labouriau, and M. T. Sorensen. 2014. Mechanistic model to predict colostrum intake based on deuterium oxide dilution technique data and impact of gestation and prefarrowing diets on piglet intake and sow yield of colostrum. J. Anim. Sci. 92:5507-5519. doi: 10.2527/jas2014-7841

Tuchscherer, M., B. Puppe, A. Tuchschere, and U. Tiemann. 2000. Ealy identification of neonates at risk: traits of newborn piglets with respect to survival. Therio. 54:371-388. doi: 10.1016/S0093-691X(00)00355-1

van den Bosch, M., J. Wijnen, I. B. van de Linde, A. A. M. van Wesel, D. Melchior, B. Kemp, H. van den Brand, and C. Clouard. 2019. Effects of maternal dietary nitrate supplementation on farrowing and placental characteristics, level of asphyxiation at birth and piglet vitality. Therio. 129:1-7. doi: 0.1016/j.theriogenology.2019.01.033

van Dijk, A. J., T. van der Lende, and M. A. Taverne. 2006. Acid-base balance of umbilical artery blood of liveborn piglets at birth and its relation with factors affecting delivery of individual piglets. Therio. 66:1824-1833. doi: 10.1016/j.theriogenology.2006.04.035

van Dijk, A. J., B. van Rens, T. van der Lende, and M. A. M. Taverne. 2005. Factors affecting duration of the expulsive stage of parturition and piglet birth intervals in sows with uncomplicated, spontaneous farrowings. Therio. 64:1573-1590. doi: 10.1016/j.theriogenology.2005.03.017

Vanderhaeghe, C., J. Dewulf, A. de Kruif, and D. Maes. 2013. Non-infectious factors associated with stillbirth in pigs: a review. Anim. Reprod. Sci. 139:76-88. doi: 10.1016/j.anireprosci.2013.03.007

Table 5-1 Population statistics of total born piglets[1]

	Mean	Min	Max	NA[2]
Total born[3], n	16.9	4	24	0
Stillborn rate[3], %	6.4	0.0	31.3	0
pH	7.43	6.49	7.94	7
pCO_2, mmHg	39.8	9.8	131.0	6
Log pCO_2, mmHg	3.63	2.28	4.88	6
pO_2, mmHg	38	14	191	1
Log pO_2, mmHg	3.75	2.64	5.25	1
HCO_3, mmol/L	25.9	3.7	39.6	11
Base excess, mmol/L	1.59	-30.0	20.0	12
sO_2, mmol/L	71.4	13.0	100.0	10
TCO_2, mmol/L	27.2	4.0	41.0	13
Na, mmol/L	124.3	99.0	144.0	2
K, mmol/L	7.0	2.8	9.1	21
iCa, mmol/L	1.57	0.65	2.60	1
Glucose, mg/dL	43	19	566	5
Log glucose, mg/dL	3.63	2.94	6.33	5
Hematocrit, % PCV	22.2	14	45	21
Hemoglobin, g/dL	7.6	5.0	13.6	23
Birth weight, g	1,256	290	2,250	0
24 h weight, g	1,373	310	2,590	69
Wean weight, kg	4.83	1.72	8.12	191

[1] Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed by a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Number of pigs with a value not reported from the iStat portable clinical analyzer, or missing weights due to mortality.

[3] Total born and stillborn rate by sow.

Table 5-2 Effects of live-born or stillborn on blood criteria[1]

	Live-born	Stillborn	SEM	*P*-value
n	623	33	--	--
pH	7.45	6.98	0.01	< 0.001
pCO_2, mmHg	37.0	51.9	--[2]	< 0.001
pO_2, mmHg	42.5	42.5	--[3]	0.980
HCO_3, mmol/L	26.5	16.9	0.37	< 0.001
Base excess, mmol/L	2.4	-13.6	0.45	< 0.001
sO_2, mmol/L	72.3	54.4	1.29	< 0.001
TCO_2, mmol/L	27.6	18.8	0.38	< 0.001
Na, mmol/L	124.7	120.5	0.61	0.004
K, mmol/L	6.9	7.8	0.16	0.004
iCa, mmol/L	1.6	1.8	0.03	< 0.001
Glucose, mg/dL	38.9	126.1	--[4]	< 0.001
Hematocrit, %PCV	22.3	23.5	0.41	0.128
Hemoglobin, g/dL	7.6	8.0	0.13	0.094
Birth weight, g	1,282	1,148	31.4	0.019
Birth order ranking[5]	0.48	0.80	0.01	< 0.001

[1] Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Log transformation used for analysis. Log transformed means were 3.61 and 3.95 for born alive and stillborn, respectively. SEM was 0.02.

[3] Log transformation used for analysis. Log transformed means were 3.75 for born alive and stillborn. SEM was 0.04.

[4] Log transformation used for analysis. Log transformed means were 3.60 and 4.30 for born alive and stillborn, respectively. SEM was 0.03.

[5] Birth order ranking was calculated for each pig as: [(pig birth order-1)/(total born -1)].

Table 5-3 Effects of umbilical cord status at birth on blood criteria[1]

	Intact	**Ruptured**	**SEM**	***P*-value**
n	551	105	--	--
Stillborn, n	23	10	--	--
Born alive, n	528	95	--	--
pH	7.44	7.38	0.02	0.013
pCO_2, mmHg	37.7	37.0	--[2]	0.545
pO_2, mmHg	42.1	44.7	--[3]	0.263
HCO_3, mmol/L	26.3	24.7	0.68	0.016
Base excess, mmol/L	2.1	-0.1	0.91	0.016
sO_2, mmol/L	71.8	70.1	2.32	0.459
TCO_2, mmol/L	27.5	25.9	0.68	0.017
Na, mmol/L	124.4	124.9	0.97	0.567
K, mmol/L	7.0	6.8	0.23	0.495
iCa, mmol/L	1.6	1.6	0.04	0.477
Glucose, mg/dL	43.4	42.5	--[4]	0.470
Hematocrit, %PCV	22.1	23.7	0.58	0.001
Hemoglobin, g/dL	7.5	8.0	0.19	0.005
Birth weight, g	1,278	1,261	43.1	0.617
Birth order ranking[5]	0.47	0.60	0.03	< 0.001

[1] Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Log transformation used for analysis. Log transformed means were 3.61 and 3.63 for ruptured and intact, respectively. SEM was 0.04.

[3] Log transformation used for analysis. Log transformed means were 3.80 and 3.74 for ruptured and intact, respectively. SEM was 0.06.

[4] Log transformation used for analysis. Log transformed means were 3.70 and 3.61 for ruptured and intact, respectively. SEM was 0.05.

[5] Birth order ranking was calculated for each pig as: [(pig birth order-1)/(total born -1)].

Table 5-4 Effects of farrowing assistance on blood criteria at birth[1]

	Unassisted	**Assisted**	**SEM**	***P*-value**
n	543	113		
pH	7.44	7.37	0.01	< 0.001
pCO_2, mmHg	36.2	37.0	--[2]	0.938
pO_2, mmHg	44.7	36.9	--[3]	< 0.001
HCO_3, mmol/L	26.4	24.3	0.42	< 0.001
Base excess, mmol/L	2.3	-0.9	0.53	< 0.001
sO_2, mmol/L	73.5	62.1	1.28	0.010
TCO_2, mmol/L	27.6	25.5	0.42	< 0.001
Na, mmol/L	125.0	121.9	0.63	0.001
K, mmol/L	6.9	6.9	0.16	0.83
iCa, mmol/L	1.6	1.7	0.03	< 0.001
Glucose, mg/dL	40.8	55.3	--[4]	< 0.001
Hematocrit, %PCV	22.5	21.4	0.41	0.021
Hemoglobin, g/dL	7.6	7.3	0.13	0.036
Birth weight, g	1,269	1,311	32.3	0.215
Birth order ranking[5]	0.48	0.58	0.01	0.002

[1] Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Log transformation used for analysis. Log transformed means were 3.61 and 3.59 for unassisted and assisted, respectively. SEM was 0.02.

[3] Log transformation used for analysis. Log transformed means were 3.80 and 3.60 for unassisted and assisted, respectively. SEM was 0.04.

[4] Log transformation used for analysis. Log transformed means were 3.61 and 3.81 for unassisted and assisted, respectively. SEM was 0.03.

[5] Birth order ranking was calculated for each pig as: [(pig birth order-1)/(total born -1)].

Table 5-5 Effects of umbilical cord blood measurements at birth and piglet characteristics on piglet survival to 24 h[1]

	Mortality	Alive at 24 h	SEM	*P*-value
n	38	585	--	--
pH	7.35	7.46	0.03	< 0.001
$p\mathrm{CO}_2$	42.5	37.3	--[2]	0.002
$p\mathrm{O}_2$	36.6	42.5	--[3]	0.099
HCO_3, mmol/L	24.2	26.6	0.96	0.011
Base excess, mmol/L	-1.5	2.7	1.26	0.001
$s\mathrm{O}_2$, mmol/L	63.3	72.9	3.48	0.005
TCO_2, mmol/L	25.4	27.7	0.97	0.014
Na, mmol/L	122.3	124.8	1.41	0.068
K, mmol/L	6.8	6.9	0.32	0.770
iCa, mmol/L	1.7	1.6	0.06	0.018
Glucose, mg/dL	34.9	39.9	--[4]	0.008
Hematocrit, %PCV	22.5	22.3	0.81	0.736
Hemoglobin, g/dL	7.7	7.6	0.26	0.684
Birth weight, g	1,023	1,299	56.9	< 0.001
Birth order ranking[5]	0.55	0.47	0.05	0.133

[1] A total of 623 live-born pigs were used in analysis for survival to 24 h of life. Umbilical cord blood was collected from a total of immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Log transformation used for analysis. Log transformed means were 3.80 and 3.59 for mortality and alive at 24 h, respectively. SEM was 0.05.

[3] Log transformation used for analysis. Log transformed means were 3.60 and 3.79 for mortality and alive at 24 h, respectively. SEM was 0.09.

[4] Log transformation used for analysis. Log transformed means were 3.50 and 3.61 for mortality and alive at 24 h, respectively. SEM was 0.06.

[5] Birth order ranking was calculated for each pig as: [(pig birth order-1)/(total born -1)].

Table 5-6 Effects of umbilical cord blood measurements at birth and piglet characteristics on survival to weaning[1]

	Mortality	Weaned	SEM	*P*-value
n	158	465		
pH	7.40	7.47	0.01	< 0.001
pCO_2, mmHg	37.7	36.6	--[2]	0.279
pO_2, mmHg	42.1	42.5	--[3]	0.899
HCO_3, mmol/L	24.5	27.1	0.53	< 0.001
Base excess, mmol/L	-0.31	3.31	0.67	< 0.001
sO_2, mmol/L	68.7	73.5	1.94	0.010
TCO_2, mmol/L	25.8	28.2	0.55	< 0.001
Na, mmol/L	122.8	125.3	0.83	0.001
K, mmol/L	6.93	6.89	0.20	0.822
iCa, mmol/L	1.63	1.54	0.04	0.003
Glucose, mg/dL	36.6	40.1	--[4]	< 0.001
Hematocrit, %PCV	22.3	22.3	0.51	0.984
Hemoglobin, g/dL	7.6	7.6	0.17	0.946
Birth weight, g	1,052	1,355	35.9	< 0.001
24 h weight, g	1,101	1,469	41.6	< 0.001
Birth order ranking[5]	0.50	0.47	0.024	0.343

[1] A total of 623 live-born pigs were used in analysis for survival to wean. Umbilical cord blood was collected from a total of immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Log transformation used for analysis. Log transformed means were 3.63 and 3.60 for mortality and weaned, respectively. SEM was 0.03.

[3] Log transformation used for analysis. Log transformed means were 3.74 and 3.75 for mortality and weaned, respectively. SEM was 0.05.

[4] Log transformation used for analysis. Log transformed means were 3.53 and 3.64 for mortality and weaned, respectively. SEM was 0.04.

[5] Birth order ranking was calculated for each pig as: [(pig birth order-1)/(total born -1)].

Table 5-7 Effects of birth order ranking category on umbilical cord blood measurements at birth[1,2]

	Birth order ranking category					
	< 0.25	0.25-0.50	0.51-0.75	> 0.75	SEM	*P*-value
n	182	162	147	165	--	--
pH	7.52^{a}	7.46^{b}	7.41^{c}	7.31^{d}	0.02	< 0.001
$p\mathrm{CO}_2$, mmHg	34.5^{b}	37.7^{a}	37.7^{a}	40.4^{a}	--[3]	< 0.001
$p\mathrm{O}_2$, mmHg	40.9^{b}	40.0^{b}	47.5^{a}	42.1^{ab}	--[4]	0.007
HCO_3, mmol/L	28.4^{a}	27.3^{a}	24.9^{b}	23.1^{c}	0.53	< 0.001
Base excess, mmol/L	5.3^{a}	3.5^{a}	0.2^{b}	-2.7^{c}	0.68	< 0.001
$s\mathrm{O}_2$, mmol/L	72.9^{ab}	70.6^{ab}	75.0^{a}	67.8^{b}	1.80	0.012
TCO_2, mmol/L	29.4^{a}	28.5^{a}	26.1^{b}	24.5^{b}	0.53	< 0.001
Na, mmol/L	125.6^{a}	125.2^{ab}	123.8^{ab}	123.1^{b}	0.78	0.01
K, mmol/L	6.7^{b}	6.6^{b}	7.3^{a}	7.3^{a}	0.19	< 0.001
iCa, mmol/L	1.47^{c}	1.54^{bc}	1.61^{ab}	1.67^{a}	0.03	< 0.001
Glucose, mg/dL	35.9^{c}	37.4^{bc}	45.6^{b}	55.4^{a}	--[5]	< 0.001
Hematocrit, %PCV	21.8^{b}	22.3^{ab}	21.9^{b}	23.4^{a}	0.49	0.002
Hemoglobin, g/dL	7.4^{b}	7.6^{ab}	7.5^{b}	8.0^{a}	0.16	0.001
Birth weight, g	1,222^{b}	1,248^{b}	1,268^{b}	1,372^{a}	36.8	< 0.001

[1] Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Birth order ranking was calculated for each pig as: [(pig birth order-1)/(total born -1)].

[3] Log transformation used for analysis. Log transformed means were 3.54, 3.63, 3.63, and 3.70 for the birth order categories < 0.25, 0.25-0.50, 0.51-0.75 and > 0.75, respectively. SEM was 0.03.

[4] Log transformation used for analysis. Log transformed means were 3.71, 3.69, 3.86, and 3.74 for the birth order categories < 0.25, 0.25-0.50, 0.51-0.75 and > 0.75, respectively. SEM was 0.05.

[5] Log transformation used for analysis. Log transformed means were 3.55, 3.58, 3.69, and 3.81 for the birth order categories < 0.25, 0.25-0.50, 0.51-0.75 and > 0.75, respectively. SEM was 0.04.

Table 5-8 Effects of cumulative birth interval category on umbilical cord blood criteria at birth[1,2]

	Cumulative birth interval, min					
	< 44	44-95	95-164	> 164	SEM	*P*-value
n	167	161	165	163		
pH	7.52^{a}	7.46^{b}	7.41^{b}	7.32^{c}	0.02	< 0.001
pCO_2, mmHg	35.5	37.7	38.5	38.9	--[3]	0.061
pO_2, mmHg	42.5	41.3	41.3	44.7	--[4]	0.473
HCO_3, mmol/L	28.8^{a}	26.9^{b}	25.3^{c}	22.7^{d}	0.56	< 0.001
Base excess, mmol/L	5.7^{a}	3.0^{b}	0.6^{c}	-2.9^{d}	0.75	< 0.001
sO_2, mmol/L	74.5	71.3	70.1	69.9	1.90	0.199
TCO_2, mmol/L	29.8^{a}	28.1^{b}	26.5^{c}	24.1^{d}	0.56	< 0.001
Na, mmol/L	126.1^{a}	125.4^{ab}	123.6^{bc}	122.6^{c}	0.80	0.001
K, mmol/L	6.5^{b}	6.9^{ab}	7.0^{ab}	7.4^{a}	0.19	< 0.001
iCa, mmol/L	1.47^{b}	1.52^{b}	1.62^{a}	1.68^{a}	0.04	< 0.001
Glucose, mg/dL	34.9^{c}	39.9^{bc}	48.1^{b}	51.5^{a}	--[5]	< 0.001
Hematocrit, %PCV	22.4	21.9	22.3	22.7	0.51	0.547
Hemoglobin, g/dL	7.6	7.5	7.6	7.7	0.16	0.624
Birth weight, g	1,215^{b}	1,252^{ab}	1,319^{a}	1,329^{a}	39.3	0.007

[1] Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Cumulative birth interval for each pig born was calculated as the time (min) elapsed from the birth of first pig until birth time of the current pig.

[3] Log transformation used for analysis. Log transformed means were 3.57, 3.63, 3.65, and 3.66 for the cumulative birth interval categories < 44, 44-95, 95-164 and > 164, respectively. SEM was 0.03.

[4] Log transformation used for analysis. Log transformed means were 3.75, 3.72, 3.72, and 3.80 for the cumulative birth interval categories < 44, 44-95, 95-164 and > 164, respectively. SEM was 0.05.

[5] Log transformation used for analysis. Log transformed eans were 3.52, 3.60, 3.69, and 3.81 for the cumulative birth interval categories < 44, 44-95, 95-164 and > 164, respectively. SEM was 0.04.

Table 5-9 Univariate associations between colostrum intake and umbilical cord hematological criteria or total born[1,2]

Response	R	*P*-value
Total born	-0.38	< 0.001
pH	0.20	< 0.001
pCO_2[3]	-0.02	0.640
pO_2[3]	-0.03	0.510
HCO_3	0.27	< 0.001
Base excess	0.25	< 0.001
sO_2	0.06	0.140
TCO_2	0.26	< 0.001
Na	0.16	< 0.001
K	-0.01	0.860
iCa	-0.09	0.029
Glucose[3]	0.01	0.019
Hct	0.09	0.024
Hb	0.10	0.021

[1] Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc.; Princeton, NJ).

[2] Colostrum intake in 24 h was calculated using the equation from Thiel et al. (2015).

[3] Log transformed values were used.