Conceptus and maternal responses to increased feed intake during early gestation in pigs[1,2]

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ABSTRACT: Maternal diet influences fetal growth and postnatal development. We hypothesized that conceptuses gestated in sows provided ad libitum vs. restricted feed intake would differ in the milieu of hormones, growth factors, nutrients, and metabolites associated with growth and metabolism. This hypothesis was tested in two experiments by providing fourth-parity sows (Pig Improvement Co. C15 bred to Line 326 boars) with either 1.81 kg/d (as-fed basis; control) or ad libitum access to gestation diet. In Exp. 1, control (n = 6) or ad libitum (6.4 ± 0.11 kg/d; n = 9) treatments were provided from d 29 to 45 (onset of estrus is d 0), and sows were slaughtered on d 46. Ad libitum sows gained more weight from d 29 to 45 than controls (34.0 vs. 4.32 kg, respectively; $P < 0.01$). No differences were observed on d 46 for the number of fetuses, conceptus attachment length, allantoic + amniotic fluid volume, placental weight, fetal weight, and fetal crown-to-rump length. Variation in fetal crown-to-rump length was less ($P < 0.03$) in sows fed ad libitum. Sows fed ad libitum had greater ($P < 0.01$) IGF-I and insulin concentrations in plasma than controls on d 43. In Exp. 2, sows were fed 1.81 kg/d (n = 6) or ad libitum (7.0 ± 0.11 kg/d; n = 4) from d 30 to 56 of gestation, when sows were anesthetized and samples were collected surgically from their gravid uteri. Sows fed ad libitum gained more weight ($P < 0.01$) than did controls and had more ($P < 0.06$) IGF-I in their plasma and the plasma collected from umbilical veins of their fetuses. No differences were found for concentrations of insulin or glucose in plasma of sows or fetuses, but urea N concentrations were greater ($P < 0.05$) in maternal plasma and in the plasma, and allantoic and amniotic fluids of conceptuses from sows fed ad libitum. Combined data from Exp. 1 and 2 revealed a treatment × fetal number interaction ($P < 0.05$) for average fetal weight. The expected negative relationship between within-litter average fetal weight and the number of fetuses per uterus was observed for control sows ($y = 115.4 - 1.75 \times$ fetal number; $P < 0.05$), but litters of ad libitum sows did not show this effect. The hypothesis that providing feed in excess of established requirements in early gestation affects the in utero milieu is supported by these results. Data further reveal that, at least at mid-gestation, the restraint to fetal growth that is exhibited when fetal number increases in control sows is not exhibited when sows are fed ad libitum.

Key Words: Conceptus, Feed Intake, Insulin-Like Growth Factor, Pigs, Pregnancy

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Introduction

When fetal access to nutrients is restricted, there are many effects on postnatal development and function (Godfrey and Robinson, 1998; Barker, 1999; Hale and Ozannes, 2003). However, nutritional management of gestating farm livestock aims to meet maternal requirements for maintenance and growth in early gestation and has generally not been evaluated as a programmer of postnatal traits. In pigs, Dwyer et al. (1994) reported that postnatal growth to market weight increased when sows were fed twice the standard allocation from 25 to 50, 50 to 80, or 25 to 80 d of gestation. Furthermore, the carcass fat of the offspring was decreased. It is reasonable to assume that the response of pig conceptuses to maternal feed intake is mediated by the milieu of hormones, nutrients, growth factors, and other constituents within the gravid uterus. Therefore, we hypothesized that key regulators of growth and markers for metabolic processes would be affected by providing

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maternal feed intake above standard amounts. To evaluate this hypothesis, experiments were designed to determine the effects of ad libitum feeding during early gestation on fetal growth, and on concentrations of certain constituents of maternal and fetal plasma and conceptus fluids.

Materials and Methods

Animals

Experimental protocols were approved by the Institutional Animal Care and Use Committee at Kansas State University. Maternal line, parity-four sows (C15, Pig Improvement Co. USA, Franklin, KY) were inseminated with semen from Line 326 (PIC USA) boars. Onset of estrus was considered d 0. Sows were housed individually in gestation stalls (2.13 × 0.61 m) on solid concrete floors during the experiment. Treatments were 1.81 kg/d (as-fed basis; control) or ad libitum intake of a grain-sorghum, soybean meal diet containing 0.60% total lysine, 0.9% Ca, and 0.8% P, that met or exceeded vitamin and mineral requirements for gestating sows (NRC, 1998). Control sows were fed 1.81 kg/d at 0800, whereas sows fed ad libitum were provided (as-fed basis) 2.72 kg at 0800 and 3.62 kg feed at 2000 each day. Feeding management for ad libitum sows provided some feed in each sow's feed trough at all times. Feed not consumed by the beginning of the next meal (including any feed on the floor) was collected and weighed. All sows had ad libitum access to water provided by a nipple waterer in each stall.

Experiment 1

All sows were provided 1.81 kg (as-fed basis) of feed daily until d 28 of gestation. Beginning on d 29, sows either continued to receive 1.81 kg/d of diet (control, n = 6) or were provided ad libitum feed (n = 9) until d 46 of gestation. Sows were weighed on d 29 and 45 and slaughtered on d 46 of gestation. Blood was collected into heparinized tubes from sows on d 43 by puncture of the anterior vena cava 2 h after each feeding. Blood samples were placed on ice until centrifuged (4,000 × *g*, 30 min at 5°C), and plasma was harvested and stored at –15°C.

Sows were slaughtered by captive bolt stunning and exsanguination. Gravid uteri were collected, and extraembryonic fluid (allantoic + amniotic) was collected after puncturing the membranes. Fluid volume (to the nearest 1 mL) was measured in a graduated cylinder. Extraembryonic membranes and fetuses were individually weighed, and the length of each fetus (crown to rump) was measured. The length of the attachment site of each placenta, as indicated by the vascularity of the endometrial surface, was measured.

Experiment 2

Sows were fed from d 30 to 56 of gestation the same control or ad libitum amounts of diet used in Exp. 1. The treatment period was extended to d 56 of gestation (compared with d 46 in Exp. 1) to allow collection of sufficient umbilical blood for assays. Maternal blood was collected from the anterior vena cava on d 29 and 56 at 3 h after the morning feeding. After blood collection on d 56, sows were anesthetized with sodium pentathol (Abbott Laboratories, North Chicago, IL; 5%, 35 to 50 mL i.v.) and atropine sulfate (Phoenix Pharmaceutical, St. Joseph, MO; 0.054%, 5 mL, i.m.) was administered to inhibit salivation. Halothane (Halocarbon Laboratories, River Edge, NJ) was applied by inhalation to maintain anesthesia.

The reproductive tract was exposed through a ventral midline incision and branches of the uterine artery and uterine ovarian vein were cannulated with 21-gauge, 19-mm winged needles attached to 30 cm of flexible tubing (Terumo, Tokyo, Japan). Blood was drawn simultaneously into two 12-mL syringes. Collection of conceptus samples started with the fetus at the tip of the right uterine horn, and continued sequentially to the uterine body and then anteriorly in the left horn, until all conceptuses were sampled. Allantoic and amniotic fluid samples were collected by puncture through the uterine wall with an 18-gauge, 3.8-cm needle attached to a 12-mL syringe. The umbilical cord was exposed through an incision, and umbilical-vein blood was collected through a 20-gauge needle attached to a 12-mL syringe. Blood samples were divided equally into tubes containing heparin or oxaloacetate and kept on ice until centrifuged (4,000 × *g*, 30 min at 5°C). Plasma was harvested and stored (–15°C).

After collection of blood and fluids, the fetus was removed, weighed, crown-rump length measured, and the liver removed and weighed. Fluids and plasma samples were assayed for urea N, IGF-I, insulin, and glucose. Following removal of the last fetus a complete ovariohysterectomy was performed, the incision was closed using standard procedures, and the sow allowed to recover. The number of corpora lutea (**CL**) on each ovary was counted and each CL was bisected to detect adjacent fused CL.

Assay Procedures. Fetal pigs were frozen, ground, and total protein (AOAC, 1995: 992.23), fat (AOAC, 1995: 985.14), ash (AOAC, 1995: 925.11), and moisture (AOAC, 1995: 926.07) were determined. Urea N concentrations were determined with an autoanalyzer (Alpkem, Clackamas, OR) according to procedures described by Marsh et al. (1965). Glucose concentrations were determined using a kit (Sigma Chemical Co., St. Louis, MO). The sample was added to a mixture of glucose oxidase, peroxidase, and *o*-dianisidine, and color intensity was measured (Raabo and Terkildsen, 1960). The assay had 95 to 112% recovery, with a CV of 3.4%.

Plasma concentrations of total IGF-I were determined using a commercially available two-site immunoradiometric assay (Active IGF-I with extraction, DSL-5600, Webster, TX) previously validated for por-

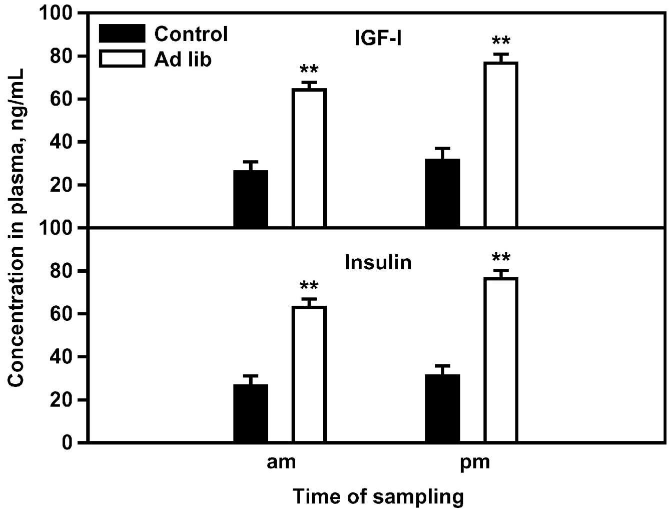

Figure 1. Plasma IGF-I and insulin of sows in Exp. 1. Blood samples were collected 2 h after the morning and evening meals on d 43 of gestation. **Ad libitum feeding increased ($P < 0.01$) concentrations of IGF-I and insulin in plasma. No effects of time of sampling (a.m. vs. p.m.) or its interaction with treatment were detected.

cine plasma (Balaji et al., 2000). Intra- and interassay CV for IGF-I were 3.0 and 3.9%, respectively.

Insulin was measured using commercially available reagents (Diagnostic Products Corp., Los Angeles, CA; product No. TKIN1). To validate the assay for use in porcine serum, insulin standard was added to a pool of porcine serum to achieve 0.45, 0.65, 1.38, 2.42, and 4.50 ng/mL, and 0.45, 0.76, 1.59, 2.57, and 4.49 ng/mL, respectively, was measured in the assay. Thus, the regression of concentration measured on concentration expected had a slope of 0.99 and the 95% confidence interval for the slope included 1.0. Additionally, dilutions of porcine serum of 1:1, 1:1.33, and 1:2 yielded similar concentration when corrected for dilution. The regression of concentration measured in each dilution on concentration expected had a slope of –0.006 and the 95% confidence interval for the slope included 0. Observed intra- and interassay CV for insulin were 4.9 and 16.9%, respectively.

Statistical Analyses. Data were analyzed using the GLM procedure of the SAS (SAS Inst., Inc., Cary, NC). Sow was the experimental unit, and values reported are least squares means ± SEM. Sow BW at the start of the experiment (d 29 in Exp. 1 and d 30 in Exp. 2) was used as a covariate for BW gain. In Exp. 2, concentrations of metabolites and hormones on d 29 of gestation (before treatments were applied) were used as covariates in analyses of concentrations on d 56. Variation of the mean was tested using Levene's test (Milliken and Johnson, 1984). In this test, the residuals for each observation (absolute value of the difference between the observation and the litter mean) are subjected to analysis of the variance. Estimates of variation are reported if $P \leq 0.10$.

Results

Experiment 1

Ad libitum-fed sows had increased ($P < 0.05$) IGF-I and insulin concentrations in their plasma on d 43 of gestation (Figure 1) and increased weight gain from d 29 to 45 ($P = 0.005$; Table 1) compared with controls. No differences were observed in the number of fetuses per sow, attachment length, allantoic + amniotic fluid volumes, placental and fetal weights, or fetal crown-to-rump lengths.

Residuals were tested to estimate the within-litter variation of fetal and placenta weight and crown-to-rump length. No differences were observed for measures of placental size or fetal weight, but fetal crown-

Table 1. Sow and fetal performance after limited or ad libitum feeding from d 29 to 45 of gestation in Exp. 1

	Feed intake			
Variable	1.81 kg/d	Ad libitum	SEM	$P <$
No. of sows	6	9	—	—
Sow daily feed intake, kg/d (as-fed basis)	1.81	7.0	0.11	0.01
Sow weight gain, kg	4.32	34.00	10.57	0.005
No. of fetuses	9.83	11.33	3.45	0.57
No. of mummies	3.33	2.67	1.34	0.57
Attachment length, mm	157.7	191.9	27.46	0.36
Allantoic + amniotic fluid volume, mL	32.49	34.13	3.27	0.88
Fetal weight, g	21.08	18.39	3.06	0.38
Placental weight, g	64.03	61.41	3.73	0.81
Crown-rump length, mm	69.26	67.24	3.90	0.57
Crown-rump length variation, mm[a]	4.77	3.17	0.60	0.03

[a]Variation estimated as the absolute value of the deviation from the mean of litter for each birth weight. Residuals were evaluated for treatment variation by analysis of variance (Levene's test; Milliken and Johnson, 1984).

Table 2. Responses of sows to ad libitum feed from d 30 to 56 of gestation in Exp. 2

Variable	Feed intake: 1.81 kg/d	Feed intake: Ad libitum	SEM	$P <$
No. of sows	6	4	—	—
Sow daily feed intake, kg/d (as-fed basis)	1.81	7.0	0.11	0.01
Sow weight gain, kg	2.11	41.2	2.5	0.01
Fetuses per sow	11.67	10.50	2.25	0.70
Plasma urea N, mg/dL				
d 29	7.50	7.25	0.97	0.84
d 56[a]	8.26	12.89	1.00	0.01
IGF-I, ng/mL				
d 29	60.07	88.49	9.77	0.05
d 56[a]	45.10	91.98	15.00	0.06
Insulin, ng/mL				
d 29	0.89	0.71	0.11	0.24
d 56[a]	0.94	0.85	0.17	0.71
Sow glucose, mg/dL				
d 29	79.1	75.9	4.04	0.54
d 56[a]	81.2	82.6	4.30	0.81

[a]Measurement at d 29 was used as a covariate for statistical analysis.

to-rump length variation was less ($P < 0.05$) for fetuses from sows fed ad libitum.

Experiment 2

Sows fed ad libitum gained more ($P < 0.01$) weight from d 30 to 50 of gestation than control sows (Table 2). On d 29, before initiation of treatments, sows assigned to the ad libitum treatment had greater ($P < 0.05$) concentrations of IGF-I in their plasma. Apparently, this occurred due to chance assignment of sows with higher IGF-I to this treatment, and concentrations of IGF-I measured on d 56 were analyzed using the d-29 concentrations as a covariate. On d 56, ad libitum-fed sows had greater ($P < 0.05$) concentrations of IGF-I in maternal plasma collected from the vena cava, uterine artery, uterine vein (Figure 2), and in their fetuses' plasma ($P = 0.06$; Figure 3) than did controls. The number of fetuses per sow (Table 2) and fetal weight and length (Table 3) were not affected by maternal feed intake. Fetal moisture, protein, fat, and ash expressed as percentages of fetal weight were not affected by maternal treatment; however, weights of fetal livers were increased ($P < 0.04$) for ad libitum-fed sows.

Increased ($P < 0.01$) concentrations of urea N were observed for the plasma of ad libitum-fed sows (Figure 2), and their conceptuses had greater ($P < 0.01$) concentrations of urea N in their plasma, allantoic fluid, and amniotic fluid than controls (Figure 4). No treatment effects on insulin or glucose concentrations in plasma were observed for sows or fetuses except that glucose in the allantoic fluid was less ($P = 0.06$) for conceptuses of ad libitum sows.

Fetal Number and Average Fetal Weight

The relationship between fetal number and within-litter average fetal weight was evaluated by regression analysis (Figure 5). In Exp. 1, control fetuses demonstrated a tendency for a negative relationship between the number of fetuses per uterus and fetal weight ($r^2 = 0.48$; $P = 0.15$), but fetuses from ad libitum-fed sows did not exhibit this relationship ($r^2 = 0.003$). A tendency for a negative relationship between number of fetuses per uterus and average fetal weight was also observed for control sows in Exp. 2 ($r^2 = 0.43$; $P = 0.17$), but fetuses in ad libitum-fed sows did not show this relationship ($r^2 = 0.14$). Fetuses were collected on d 46 in Exp. 1 and on d 56 in Exp. 2. This resulted in a 77.5-g difference in mean fetal weight. To combine the fetal

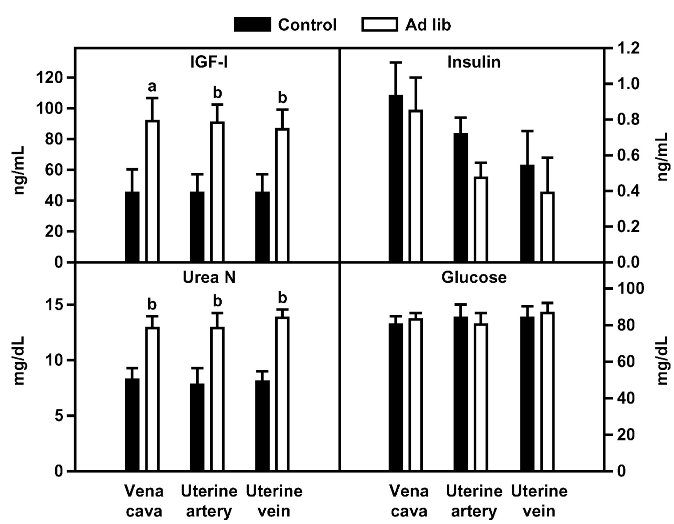

Figure 2. Effect of treatments on constituents in plasma of sows on d 56 of gestation in Exp. 2. [a]Ad libitum feeding tended ($P = 0.06$) to increase IGF-I in the vena cava and increased ($P < 0.05$) IGF-I in the uterine artery and vein. [b]Ad libitum feeding increased ($P < 0.05$) urea N in the vena cava, uterine artery, and uterine vein.

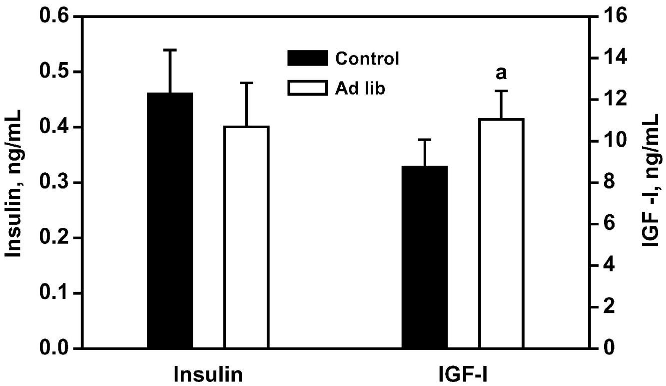

Figure 3. Concentrations of insulin and IGF-I in the fetal umbilical vein (Exp. 2). [a]Ad libitum feeding tended (P = 0.06) to increase IGF-I.

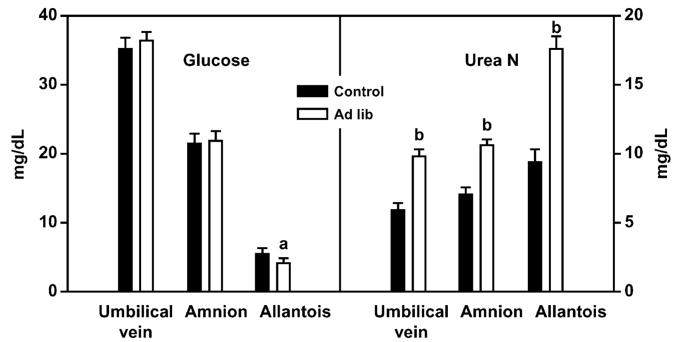

Figure 4. Glucose and urea N in plasma in the umbilical vein and in the amnion and allantoic fluids on d 56 of pregnancy (Exp. 2). [a]Glucose was decreased (P < 0.06) in allantoic fluid, and urea N was increased (P < 0.01) in the umbilical vein, the amniotic fluid, and the allantoic fluid by ad libitum feeding.

weights for the two experiments in one analysis, 77.5 g was added to the average fetal weight of each litter in Exp. 1. Analysis of the combined data revealed a treatment × fetal number interaction (P < 0.05). For control litters, there is a negative relationship between fetal number and average fetal weight (r^2 = 0.42, P < 0.05). No relationship was found between fetal number and average fetal weight in ad libitum-fed sows.

Discussion

Increasing maternal feed intake altered maternal physiology by increasing concentrations of IGF-I and urea N in plasma. The conceptuses in ad libitum-fed sows also had greater concentrations of IGF-I in their plasma and more urea N in their plasma, allantois and amnion. Furthermore, the fetuses in ad libitum sows had larger livers. These results support the hypothesis that the milieu on both the maternal and the conceptus sides of the placenta is affected by increased feed intake in gestating sows.

Maternal treatment with porcine ST (**pST**) increased both maternal and fetal IGF-I and tended to increase fetal IGF-II (Sterle et al. 1995). Therefore, pST and the nutritional treatment reported here may act through mechanisms involving maternal and/or fetal IGF-I to alter within litter growth of fetuses. However, a comparison of observations in Exp. 2 to the report of Gatford et al. (2000) reveals substantial differences in the response of pregnant pigs to exogenous pST and increased maternal feed.

Table 3. Fetal characteristics on d 56 of gestation, as affected by maternal feed intake (as-fed basis) from d 30 to 56 of gestation in Exp. 2

	Feed intake			
Variable	1.81 kg/d	Ad libitum	SEM	P <
No. of fetuses	70	42	—	—
Fetal weight, g	96.6	97.9	3.69	0.76
Fetal length, mm	120.11	119.58	1.73	0.78
Fetal composition, %				
Moisture	89.71	89.03	0.38	0.20
Protein	6.51	6.57	0.11	0.69
Fat	0.86	0.89	0.27	0.92
Ash	1.97	2.00	0.12	0.82
Fetal liver weight, g	5.50	6.39	0.36	0.04

Gatford et al. (2000) fed gilts (141.8 kg BW) 1.8 kg/d of a diet similar in protein and energy composition to the one used in Exp. 1 and 2, and injected the gilts with 0, 2, or 4 mg of pST daily from d 25 to 50 of pregnancy. Exogenous pST resulted in increased concentrations of IGF-I in maternal plasma, a response similar to the greater maternal IGF-I observed in response to increased maternal feed in Exp. 1 and 2. However ad libiltum feed intake increased maternal weight and plasma urea N (Exp. 1 and 2), but exogenous pST did not have these effects (Gatford et al., 2000). Comparison of conceptus responses reveals that pST increased fetal weight and fetal plasma glucose, responses not observed following increased maternal feed in the present report. Furthermore, increased maternal feed resulted in increased concentrations of urea N and IGF-I in fetal plasma (Exp. 2), whereas maternal pST treatment did not affect fetal IGF-I and decreased the concentration of urea N in fetal plasma (Gatford et al., 2000). Both pST and increased maternal feed increased fetal liver weights. Therefore, although both pST and ad libitum maternal feed increase maternal IGF-I, the two treatments seem to differ substantially in their effects on fetal physiology. An understanding of the conceptus responses to these and other maternal treatments is needed.

The increased weight of fetal livers for ad libitum-fed sows in Exp. 2 could be associated with a response to detoxify elevated ammonia if it is present. Maternal IGF-I is not known to cross the placental barrier (Underwood et al., 1979), and it may be that increased

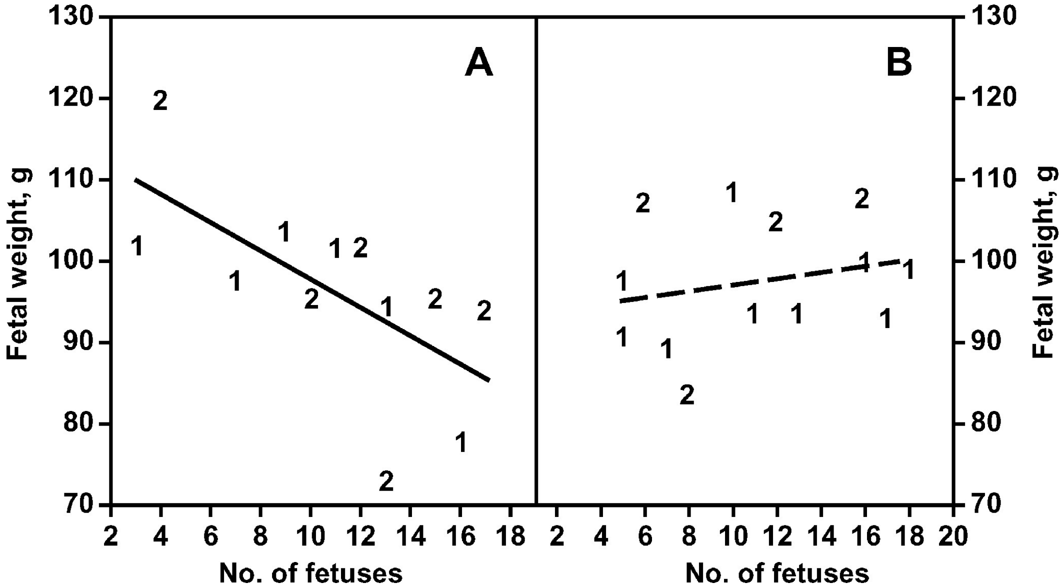

Figure 5. The relationship between the number of fetuses per sow and average fetal weight in Exp. 1 and 2 is given (corresponding numbers in the graphs indicates data points for Exp. 1 and 2). Analysis of the combined data from Exp. 1 and 2 revealed an interaction ($P < 0.05$) between fetal number and treatment. Panel A) For sows fed 1.81 kg/d, there is a negative relationship ($P < 0.05$) between fetal number and average fetal weight for combined Exp. 1 and 2; y = 115.4 − (1.75 × fetal number). Panel B) For sows fed ad libitum, the relationship between fetal number and average fetal weight was not significant; y = 92.6 + (0.43 × fetal number).

weight of fetal livers is associated with increased IGF-I production; however, liver is not the predominant source of IGF-I in fetal pigs (Lee et al., 1993; Peng et al., 1996).

Fetal glucose was not altered by maternal feed intake. This might be expected due to the homeostatic regulation of circulating concentrations of glucose, and the 3-h interval from feeding to sample collection. However, it is known that the ungulate fetus converts glucose to fructose (Alexander et al., 1966), and pig fetuses have relatively large amounts of fructose in their blood (Pere, 1995; 2001). Fetuses from ad libitum-fed sows also had lower concentrations of glucose in their allantoic fluids, but an explanation for this effect is not evident.

These observations on fetal development contrast with those reported when peripubertal ewes are overfed in gestation. At gestation d 128, the fetuses of overfed adolescent ewes were smaller and had decreased insulin, IGF-I, and urea N. In addition, their livers were lighter and contained less glycogen (Wallace et al., 2000). These effects of maternal overfeeding in sheep stand in contrast to those observed for sows in Exp. 2. The response in peripubertal ewes has been interpreted to represent the stimulation of maternal growth at the expense of the conceptus. Therefore, the dichotomy in the responses observed in Exp. 2 and those reported for the peripubertal ewe could reflect the physiological differences associated with reproductive age of the dam (peripubertal ewes vs. fourth-parity sows in Exp. 2). However, we cannot exclude the possibility that the relatively later time of measurement during gestation (d 128 of an expected 145 d gestation) in the report of Wallace et al. (2000) revealed changes not yet evident in the swine pregnancies in Exp. 2 (d 56 of an expected 115 d gestation).

The sheep fetuses of adolescent dams that are overfed are smaller at birth (Wallace et al., 1996, 1997). In swine, Musser et al. (2003) compared sows of mixed parities that were fed 1.81 or 3.63 kg/d of complete diet from d 30 to 50 of gestation and then fed similarly for the remainder of gestation (1.8 kg/d until d 100 and then 2.72 kg/d until farrowing). The increased amount of complete diet from d 30 to 50 resulted in a reduction in the number of pigs per litter, but litter birth weights were not affected. Therefore, there was no indication that total conceptus mass in sows responds to overfeeding in a manner similar to the severe decrease in fetal weight of singleton lambs in the reports of Wallace et al. (1996, 1997). Whether these differences represent species differences or differences in the physiological maturity of the dam will require further study.

Another treatment in the experiment by Musser et al. (2003) provided supplemental ground corn (1.81 kg/d) from d 30 to 50 and resulted in litter sizes at term similar to those of controls, but greater than for sows fed an additional 1.81 kg/d of complete diet. Therefore, specific components of the complete diet may have been responsible for the detrimental effect on litter size when the complete diet was increased above standard amounts (Musser et al., 2003). The increased urea N in the fetal compartment observed in Exp. 2 may indicate that dietary protein contributed to this effect. Some of the urea N in conceptuses may have crossed the placenta from the maternal plasma; however, it is likely that at least some of the increased fetal urea N resulted from ammonia produced by deamination of excess AA in the fetal compartment. If so, this raises the possibility that ammonia concentrations in the fetal compartment of ad libitum-fed sows could reach levels that affected metabolism and growth. If fetal ammonia concentrations are excessive, the combined results of Exp. 2 and Musser et al. (2003) indicate that their negative effects on fetal survival become evident after d 56 and before term. Further, because Musser et al. (2003) observed no effects on the number of mummified fetuses at term, it is likely the decrease in litter size occurs in the middle third of gestation, when their small size makes mummified fetuses unlikely to be detected at farrowing.

Figure 5 shows the data from Exp. 1 and 2 after adding 77.5 g to the weights of fetuses from Exp. 1 to compensate for their younger gestational age. This adjustment seems valid because there were no treatment effects on fetal weight in either experiment, and the mean fetal weights for the two experiments differed by 77.5 g. The 77.5-g difference in fetal weight between the two gestational ages is virtually identical to the difference in these gestational ages (45 and 56 d) calculated from the data of Marrable and Ashdown (1967).

The data in Figure 5 reveal a treatment effect on the relationship between the number of fetuses per uterus and the average fetal weight. In litter-bearing species, it is expected that increasing the number of fetuses in a uterus results in decreased average weight for individual fetuses, and this effect has been referred to as a "maternal constraint" (Gluckman et al., 1992). Results for control sows in both Exp. 1 and 2 were consistent with the presence of maternal constraint; however, ad libitum-fed sows did not show any relationship between fetal number and average fetal weight, and fetuses in litters of four had similar average weights as those gestated in litters of 16. An understanding of this effect might have important implications for manipulating fetal growth in agricultural species.

Feeding sows ad libitum increased maternal IGF-I. In other litter-bearing species, Gluckman et al. (1992) and Woodall et al. (1996) have shown that administration of exogenous IGF-I to pregnant rats and mice abolishes the maternal constraint within a litter at term. Perhaps the benefit was maintained to term in these experiments because negative effects of high feed intake of the dam, observed when extra amounts of complete diet are fed to the dam (Musser et al., 2003), were not present. It seems that increased maternal IGF-I in some way facilitates nutrient flow to the advantage of the smaller fetuses. The present results indicate that maternal IGF-I concentrations are associated with altering the maternal constraint in ad libitum-fed sows. Nonetheless, other factors may be involved, and the design of the present studies does not establish cause and effect.

Other data supporting an association of maternal IGF-I and fetal growth in pigs come from studies evaluating the effects of maternal pST treatments. Sterle et al. (1995) and Rehfeldt et al. (2001) found that treating gestating pigs with pST increased the growth of only the smaller fetuses in the litter, but this effect of pST was not seen under very crowded uterine conditions (Sterle et al., 2003).

The present data may also be considered with respect to programming fetal and postnatal myogenesis because Dwyer et al. (1994) observed that increasing the feed intake of sows during early gestation increased muscle fiber number and resulted in pigs that grew faster and were leaner at slaughter. Although other reports have produced inconsistent results (Musser et al., 2003; Nissen et al., 2003), the present data indicate that marked changes occur in the fetal compartment when ad libitum feed is provided to sows during an important period of fetal myogenesis. Increased fetal IGF-I could, at least in part, mediate effects of maternal feed intake on fetal myogenesis. Further work should be conducted to evaluate this relationship.

Implications

These experiments provide a model for evaluation of gestating sow feed intake on fetal physiology, and for evaluation of the concept of "maternal constraint" in porcine pregnancies. Increased maternal and fetal IGF-I and urea N in response to ad libitum maternal feeding warrant further study. Similarly, the lifting of the maternal constraint on fetal weight at mid-gestation in ad libitum-fed sows should be evaluated further. An improved understanding of these relationships may lead to practical treatments to enhance prenatal development and perhaps to affect postnatal production traits, including growth rate and carcass characteristics.

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