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Winter-feeding systems for gestating sheep II. Effects on feedlot performance, glucose tolerance, and carcass composition of lamb progeny[1]

A. E. Radunz,*[2] F. L. Fluharty,* I. Susin,† T. L. Felix,* H. N. Zerby,* and S. C. Loerch*[3]

*Department of Animal Sciences, The Ohio State University, Wooster 44691; and †Departamento de Zootecnia, Escola Superior de Agricultura "Luiz de Queiroz," Universidade de São Paulo, Piracicaba, São Paulo, Brazil

ABSTRACT: Mature pregnant crossbred ewes (n = 90) were used in a randomized complete block design experiment and were assigned to 1 of 3 winter-feeding systems differing in primary feed source: haylage (HL), limit-fed corn (CN), or limit-fed dried distillers grains (DDGS). Effects of these winter-feeding strategies on postweaning progeny performance were determined. Lamb progeny (n = 96) were weaned at 61 ± 4 d of age and fed a common high-concentrate diet. Lambs were assigned to feedlot pen (n = 18) based on dam mid-gestation pen. Growth rate, DMI, and ADG were determined for the first 40 d of the finishing period. At 96 ± 4 d of age, 1 wether lamb was randomly selected from each pen (n = 18) for a glucose tolerance test. The experiment was terminated, and lambs were slaughtered individually when they were determined to have achieved 0.6-cm 12th-rib fat thickness. After a 24-h chill, carcass data were collected and a 2.54-cm chop was removed from each lamb from the LM posterior to the 12th rib for ether extract analysis. Additional carcass measurements of bone, muscle, and fat from the shoulder, rack, loin, and leg were collected on 35 carcasses. At weaning, lamb BW was not different among treatments, whereas final BW tended to be greater ($P = 0.09$) for lambs from ewes fed DDGS and CN during gestation than from those fed HL. Overall lamb growth rate from birth to slaughter was not different among treatments. Lambs from ewes fed DDGS vs. CN or HL tended to have a greater initial insulin response ($P = 0.09$). Dressing percent was less ($P = 0.04$) in lambs from ewes fed DDGS, but no difference ($P = 0.16$) was detected in HCW among treatments. As expected, 12th rib fat thickness was similar among treatments, whereas LM area was largest to smallest ($P = 0.05$) in lambs from ewes fed CN, HL, and DDGS, respectively. Proportion of internal fat tended to be greatest to smallest ($P = 0.06$) in lambs from ewes fed DDGS, CN, and HL, respectively. Calculated boneless trimmed retail cuts percentage was less ($P = 0.04$) in lambs from ewes fed DDGS than CN or HL. Loin muscle weight as a percentage of wholesale cut tended ($P = 0.10$) to be greater in lambs from ewes fed CN and HL than DDGS, whereas other muscle, bone, and fat weights and proportions were similar ($P > 0.24$) among treatments. Prepartum diet during mid to late gestation of ewes altered postnatal fat and muscle deposition and may be associated with alterations in insulin sensitivity of progeny.

Key words: carcass composition, glucose tolerance, prepartum diet, sheep

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INTRODUCTION

Maternal nutrition plays a critical role in fetal growth and development and can have long-term impacts on the development of progeny. In cattle, prepartum dam energy source fed during late gestation at isoenergetic intakes resulted in changes in birth weight and postnatal fat deposition in progeny (Radunz, 2009). Similar diets when fed to gestating sheep for a longer period of gestation resulted in differences in birth weight (Radunz et al., 2011). Previous studies have established global undernutrition (Ford et al., 2007; Luther et al., 2007), and global overnutrition (Wallace et al., 2005; Zhu et al., 2008) in sheep can affect fetal growth and development; however, few studies have investigated these effects on postnatal growth and body composition.

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[2]Current address: University of Wisconsin, Department of Animal Science, 1675 Observatory Drive, Madison, WI 53706.

[3]Corresponding author: loerch.1@osu.edu

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A disturbance in fetal development can have long-term implications and may lead to programming for increased predisposition to insulin sensitivity during later postnatal life and an altered body composition (Godfrey and Barker, 2001). Overall increased adiposity, especially intramuscular triglyceride and visceral fat in humans, has been associated with decreased insulin sensitivity by muscle cells (Lewis et al., 2002). Programming of fetal muscle and fat tissue during gestation due to maternal nutrition could have implications on livestock production. The effects of maternal diets fed at isoenergetic intakes during mid to late gestation on progeny fat and muscle tissue deposition have not been investigated in sheep; therefore, the objective of this study was to investigate effects of dam dietary feed source on the growth, insulin resistance, and carcass composition of progeny. Our hypothesis was that a corn-based vs. a distillers grain-based gestation diet would increase growth of lean tissue and increase insulin sensitivity of lamb progeny, whereas results for a hay-based gestation diet would be intermediate. Effects of these diets on ewe performance are presented in a companion paper (Radunz et al., 2011).

MATERIALS AND METHODS

The Agricultural Animal Care and Use Committee of The Ohio State University approved the procedures used in this experiment.

Animals, Experimental Design, Treatments

Mature crossbred (Hampshire × Dorset) ewes (n = 90; BW = 83.1 ± 5.3 kg) were used in a randomized complete block design to determine the effects of mid- and late-gestation winter-feeding systems differing in winter-feeding systems on progeny postweaning performance, glucose tolerance, and carcass composition. Detailed procedures and results for ewe performance and preweaning lamb progeny performance are reported in a companion paper (Radunz et al., 2010). The study was conducted at the Sheep Center of the Ohio Research and Development Center, Wooster.

At approximately 80 d of gestation ewes were blocked (n = 3; heavy, medium, and light) by BW (average BW = 83.1 ± 5.3 kg); within block, ewes were stratified by BCS (average BCS = 2.9 ± 0.25), age (average age = 2.4 ± 0.41 yr), fetal number as determined by ultrasound (average fetal number = 1.7 ± 0.09 fetuses), and sire (n = 5). Ewes were housed in 18 pens. Ewes in each BW block were assigned to 6 pens with 5 ewes per pen. The 3 dietary treatments were randomly allotted to the 6 pens of ewes within each BW block, resulting in 2 pens per treatment within each block and a total of 6 pens per treatment.

Dietary treatments were 1 of 3 winter-feeding systems, which differed in primary feed source (Table 1); haylage (fiber; **HL**), limit-fed corn (starch; **CN**), and limit-fed corn dried distillers grains (fiber, fat, and protein; **DDGS**). Diets were formulated to meet or exceed NRC (1985) nutrient requirements for mid gestation (d 81 to 115) at 2.8 ME of Mcal/d and late gestation (d 115 to parturition) at 4.0 ME of Mcal/d. Intake of CN and DDGS were limited to achieve isoenergetic intake among dietary treatments relative to an ad libitum intake of haylage. A more detailed description of diets is provided in Radunz et al. (2011). Intakes of the DDGS and CN diets were adjusted if needed to maintain similar BW gain of ewes receiving these diets with ewes fed HL during mid gestation. Intake of CP was not balanced among treatments because DDGS has a greater concentration of CP, which exceeds the requirements of the gestating ewe. Furthermore, addition of protein to CN and HL diets to equal the DDGS diet would not be economically practical for winter-feeding systems for sheep. Ewes were fed dietary treatments until parturition and then were managed similarly until weaning.

Table 1. Progeny finishing diet composition (DM basis)

Item	Amount
Ingredient, %	
Ground corn	45.79
Soybean hulls	31.66
DDGS[1]	15.04
Soybean meal	4.31
Limestone	1.73
Trace mineral salt[2]	0.60
Ammonium chloride	0.60
Selenium, 201 mg/kg	0.18
Vitamin E, 44 IU/g	0.06
Vitamin A, 30,000 IU/g	0.01
Vitamin D, 3,000 IU/g	0.01
Lasalosid[3]	0.02
Nutrient composition[4]	
ME, Mcal/kg	2.41
CP, %	14.2
Ca, %	0.96
P, %	0.48

[1]DDGS = dried distillers grains.
[2]Contained 98% NaCl, 0.35% Zn, 0.28% Mn, 0.175% Fe, 0.035% Cu, 0.007% I, and 0.007% Co.
[3]Provided 34 mg of lasalosid (Alpharma Inc., Bridgewater, NJ)/kg of dietary DM.
[4]Calculated using NRC (1985).

Experimental treatments were applied only during gestation; therefore, ewes and their progeny from all 3 gestation treatments were managed the same across treatments after lambing. Ewes and lambs representing all treatments were gathered into a total of 6 pens as the lambing season progressed. One-half of pens were assigned ewes rearing singles and one-half were for ewes rearing twins. At parturition 1 same-sex twin lamb from each original mid-gestation dam pen (n = 18; 6 lambs/treatment) was randomly selected and killed within 24 h of birth to measure body composition. After lambing, ewes from all 3 gestation treatments were fed a common diet comprised of 0.7 kg of corn silage, 1.2 kg of alfalfa haylage, and 0.5 kg of dried distillers grains (all on a DM basis) to meet requirements (NRC, 1985) dur-

ing lactation. Before 2 wk of age, the lambs were tail-docked and males were castrated. At 3 wk of age, lambs were provided ad libitum access to a pelleted creep feed (consisting primarily of corn, alfalfa meal, and soybean meal) as described by Susin et al. (1995), which was provided in a self-feeder in a creep area of the pen. The results for ewe performance and progeny preweaning are presented in Radunz et al. (2011).

Lambs were weaned (61 ± 4 d of age) and assigned to the original mid-gestation pen of their dam. These 18 pens (1.5 × 4.9 m) are on expanded metal floors, and each lamb had access to at least 0.1 m of feed bunk space. Lambs were adapted to a high-concentrate finishing diet over a 1-wk period (Table 1), and initial BW was determined by a 2-d consecutive weight after weaning. Lambs were fed to ad libitum intake and feed was delivered once daily. Feed samples were taken weekly to determine DM (drying at 100°C for 24 h), and intake was recorded daily. A 40-d test period at the start of the finishing period was used to determine ADG, DMI, and feed efficiency per pen. This period was used because after 40 d, lambs were removed from pens to be slaughtered and pen data after that point would not have included all animals.

Glucose Tolerance Test

At approximately 96 ± 4 d of age, male lambs were randomly selected to represent 1 lamb per dam mid-gestation pen (n = 18; 6 lambs/treatment) for a glucose tolerance test (**GTT**). Single (n = 6) and twin (n = 12) male lambs were used for the GTT, and type of birth was balanced among treatments. Three days before the GTT, jugular blood samples were collected prefeeding and postfeeding (3 h) into Vacutainer (Becton, Dickinson and Co., Franklin Lakes, NJ) collection tubes containing EDTA to determine insulin and glucose concentrations under typical feeding conditions. For the GTT, lambs were removed from feed 24 h before glucose infusion, and 4 h later catheters were established in a jugular vein of each lamb using aseptic procedures, as described previously by Huntington et al. (1989). Lambs were housed overnight in a separate pen to recover. The next day, lambs were weighed 15 min before glucose infusion to determine bolus size (0.25 g of glucose/kg of BW, delivered in a 50% dextrose solution). Fasting values of glucose and insulin were determined at 5 and 2 min before administration of the glucose bolus. Additional blood samples were collected at 2, 5, 10, 15, 20, 30, 60, and 120 min after the glucose infusion. Before each blood sample, 4 mL of blood was collected into a syringe to clear the catheter. A new syringe was used to collect 10 mL of blood, and then blood was placed in a tube containing EDTA. The catheters were then flushed with sterile heparinized saline (9 g/L of NaCl) after collection of each blood sample. Blood samples were placed on ice for no longer than 30 min until centrifuged at 3,000 × *g* for 20 min at 4°C. Plasma was aliquoted into four 2-mL tubes, frozen in liquid nitrogen, and stored at −80°C until subsequent analysis of glucose and insulin. A colorimetric assay was used to determine plasma glucose (1070 Glucose Trinder, Standbio Laboratory, Boerne, TX) concentrations. Plasma insulin concentrations were measured using RIA, as described by Benson and Reynolds (2001).

Slaughter Procedure and Carcass Data Collection

Lambs were palpated weekly starting after 40 d on the finishing diet to estimate 12th-rib fat thickness. When a lamb was determined to have 0.6 cm of backfat, the lamb was slaughtered at The Ohio State University Meat Science Laboratory. Final BW was calculated from weights taken on 2 consecutive days before slaughter. Kidney, pelvic, and heart fat, and kidneys were removed and weighed on the slaughter floor before measurement of HCW. Mesenteric fat and liver were removed from viscera and weighed. Carcasses were chilled (4°C) for 24 h and then ribbed between the 12th and 13th ribs. At the 12th rib interface, backfat thickness, body wall thickness, and LM area were measured. Visual lean score, leg score, conformation score, and quality grade ($Prime^{+}$ = 15; Cull = 1) were estimated according to USDA guidelines (USDA, 1992).

The LM was removed from the right side of the carcass posterior to the 12th rib. A 2.54-cm chop on the anterior end of the loin section was removed, trimmed of external fat, vacuum-packaged, and frozen (−20°C) for subsequent analysis of fat by ether extract (Ankom Technology, Fairport, NY). The remainder of the loin was vacuum-packaged, aged (4°C) for additional 6 d, and evaluated for sliced shear force (Shackelford et al., 2004). Loin sections were thawed for 24 h at 4°C before cooking. Two 2.54-cm chops from the anterior end of each loin section were removed and cooked (190°C) on an electric grill (George Foreman grilling machine, Lake Forest, IL) until chops reached an internal temperature of 71°C. Immediately after cooking, a 1-cm-thick, 2.5-cm-long slice was removed from each cooked chop parallel to the muscle fibers and laid end to end on the platform. Then, peak shear force was measured using a Texture Analyzer (TAX Texture Analyzer, Texture Technologies Corp., Scarsdale, NY), equipped with a blunt end blade attachment and crosshead speed set at 500 mm/min.

Carcass Cutout Measurements

Additional carcass measurements were collected on 35 lambs. Of those lambs, 17 were siblings to lambs slaughtered at birth to measure body composition. One lamb, whose sibling was slaughtered after birth, died shortly after weaning. These lambs at birth were randomly selected to represent 1 twin lamb per dam mid-gestation pen. Then an additional 18 lambs were randomly selected (1 from each pen representing 1 lamb per dam mid-gestation pen) to collect additional car-

cass measurements. For both groups of lambs, sex, and type of birth were balanced among treatments.

Carcasses were separated between the 12th and 13th rib into hind- and foresaddle and then weighed. The right side of the carcass was used for the remainder of the measurements and was fabricated into wholesale cuts according to the North American Meat Processors (**NAMP**) Association guidelines (NAMP, 1997). The wholesale cuts were leg (NAMP #233A), loin (NAMP #232A), rack (NAMP #207), and shoulder (NAMP #204). Weights of each wholesale cut were recorded, and cuts were dissected into muscle, fat, and bone. Dissected fat was further separated into subcutaneous and intermuscular (seam) fat. The semitendinosus and LM were excised from the wholesale cuts, weighed separately, and combined with other muscles from each respective wholesale cut to determine total muscle weight. Muscle, fat, and bone weights from each of these 4 primal cuts were combined to provide total weights of muscle, fat, and bone.

Calculations and Statistical Analysis

Glucose disappearance rate was calculated by regression of natural log-transformed glucose concentrations over time from 5 to 120 min post glucose infusion. The slope of the regression model represents the fractional clearance rate of glucose after glucose bolus infusion (k, mg·L^{-1}·min^{-1}). Incremental area under the curve (**AUC**) for insulin (min·ng^{-1}·mL^{-1}) and glucose (min·mg^{-1}·dL^{-1}) were determined using a trapezoidal summation method (Kaneko, 1989). Ratio of insulin secretion to glucose tolerance was calculated as insulin AUC divided by glucose AUC (Gardner et al., 2005). The first-phase insulin response was calculated as described by Soto et al. (2003) as the sum of 2- and 5-min insulin values minus the average of the fasting (−5 and −2 min) values.

Data were analyzed by the PROC MIXED procedure (SAS Inst. Inc., Cary, NC). Individual animal was used as the experimental unit for lambs selected to receive the GTT (n = 18), for carcass measurements (n = 96), and carcass cutout measures (n = 35) because lambs were randomly born from ewes on the 3 dietary treatments. The statistical model included dam treatment pen (n = 18) as a fixed effect. Experimental unit was pen (n = 18) for DMI, feed efficiency, and pen ADG for the finishing period because these measurements could not be determined for the individual animal. Sex, sire, and type of birth were included in the model as covariates if they represented a significant ($P < 0.10$) source of variation. When treatment was significant ($P \leq 0.05$) means were separated by the PDIFF procedure of SAS. Trends ($P > 0.05 \leq 0.10$) were also separated by PDIFF and discussed in results.

Repeated measures were used for GTT testing of the random effects of lamb and block, fixed effects of maternal diet and time (minute of sampling), and the interaction between maternal diet and time. Five covariance structures were compared for each variable (compound symmetric, autoregressive order 1, heterogeneous autoregressive order 1, spatial power, and unstructured), and the covariance structure that yielded the smallest Bayesian information criterion was used for the results presented. Simple effects within min of GTT were generated by the SLICE function in SAS.

RESULTS AND DISCUSSION

Lamb Feedlot Performance

Lamb weight was similar ($P = 0.19$) among treatments at weaning (Table 2). Final BW at slaughter tended ($P = 0.09$) to be affected by treatment; lambs from ewes fed DDGS were heaviest, those from ewes fed HL were lightest, and those from ewes fed CN were intermediate. Late-gestation dam primary feed source did not affect ($P = 0.33$) growth rate from birth to slaughter. Although ADG for the first 40 d of the finishing period was not affected ($P = 0.15$) by gestation treatment, lambs from ewes fed CN had numerically greater BW gains vs. HL or DDGS. Dry matter intake was similar among treatments ($P = 0.12$), although lambs from ewes fed CN and DDGS had numerically greater DMI (kg/d and % of BW) than lambs from ewes fed HL. Feed efficiency, time on finishing diet, and age at slaughter were similar ($P \geq 0.39$) among treatments.

In a similar study with beef cattle, growth rate, feed intake, and feed efficiency of progeny were not affected by prepartum dam diet during the last 4 mo of gestation (Radunz, 2009). Nutrient restriction during early to mid gestation has been observed to decrease postnatal BW gain (Ford et al., 2007; Husted et al., 2007). Low birth weight lambs fed ad libitum postnatally had greater feed intake in the first few weeks than their heavier birth weight counterparts, which resulted in compensatory BW gain (Greenwood et al., 2000). In those studies, differences in birth weight were larger than the present study, indicating maternal diet had minor effects on postnatal growth and appetite in lambs.

Lamb GTT

Before the GTT, basal glucose and insulin concentrations were measured pre- and postfeeding, and no differences ($P \geq 0.50$) were detected in concentration or change in concentration between pre- and postfeeding (Table 3). Fasting glucose and insulin concentrations were also similar ($P \geq 0.54$) among treatments, before glucose infusion. At 2, 5, and 10 min after infusion of glucose, glucose concentration was greater for lambs from ewes fed HL or CN than from those fed DDGS, whereas at 15 min, lambs from ewes fed HL had greater glucose concentrations than from those fed CN or DDGS (Figure 1) CORN or DDGS . Glucose tolerance (measured as glucose AUC) and glucose clearance rate were not different ($P \geq 0.52$) among treatments. These

Table 2. Effects of prepartum dam diet on progeny feedlot performance

	Treatment[1]				
Item	HL	CN	DDGS	SEM	*P*-value
Lambs (pens), n	36 (6)	33 (6)	27 (6)		
BW, kg					
Weaning	25.8	28.7	27.5	1.14	0.19
Slaughter	51.9^{y}	54.9^{xy}	58.0^{x}	1.64	0.09
ADG, kg/d					
Feedlot[2]	0.46	0.50	0.47	0.015	0.15
Overall[3]	0.40	0.42	0.41	0.011	0.33
DMI[2]					
kg/d	1.46	1.62	1.57	0.041	0.12
% of BW	4.11	3.93	4.06	0.151	0.67
G:F	0.304	0.295	0.290	0.0089	0.59
Days on feed,[4] d	60.5	56.8	61.1	3.71	0.58
Days of age,[3] d	120.3	118.2	124.6	3.52	0.39

^{x,y}Within a row, means without a common superscript differ at $P < 0.10$.
[1]HL = haylage; CN = limit-fed corn; DDGS = limit-fed dried distillers grains.
[2]Measurements collected for feedlot finishing from weaning to first group of lambs slaughtered (d = 40).
[3]Measured from birth to slaughter.
[4]Measured from weaning to slaughter.

calculations were based on glucose concentrations relative to fasting glucose concentration. Insulin concentrations were greater for lambs from ewes fed DDGS vs. HL or CN at 5, 10, and 15 min post glucose infusion (Figure 2). This was associated with lambs from ewes fed DDGS tending to have a greater ($P = 0.09$) initial insulin secretion than for lambs from ewes fed CN or HL.

Insulin resistance is defined as impaired insulin mediated glucose clearance into target tissues such as muscle, adipose, and liver cells (Leahy, 2005). Previous studies have observed alterations in insulin resistance in progeny associated with change in maternal nutrition at different stages of gestation. Nutrient restriction in late, but not early, gestation in sheep was associated with greater glucose intolerance and insulin

Table 3. Effects of prepartum dam diet on progeny glucose tolerance measurements

	Treatment[1]				
Item	HL	CN	DDGS	SEM	*P*-value
Lambs, n	6	6	6		
BW, kg	39.9	45.7	44.7	2.31	0.24
Glucose, mg/dL					
Prefeeding[2]	87.0	83.0	83.3	3.26	0.62
Postfeeding[3]	104.4	82.9	90.4	12.51	0.50
Change[4]	14.7	0.2	7.0	12.12	0.61
GTT fasting[5]	101.5	88.6	83.4	10.96	0.54
AUC,[6] min·mg^{-1}·dL^{-1}	580.2	575.1	497.4	52.63	0.52
Clearance rate, mg·L^{-1}·min^{-1}	0.076	0.083	0.077	0.0073	0.79
Insulin, ng/mL					
Prefeeding[2]	0.24	0.27	0.21	0.047	0.71
Postfeeding[3]	0.34	0.40	0.35	0.074	0.83
Change[4]	0.10	0.13	0.14	0.047	0.85
GTT fasting[5]	0.20	0.21	0.24	0.045	0.78
AUC,[6] min·ng^{-1}·mL^{-1}	2.20	3.11	4.00	0.468	0.12
Initial response,[7] ng/mL	0.86^{y}	1.02^{y}	1.63^{x}	0.204	0.09
Ratio I:G AUC,[8] ng·mg^{-1}·mL^{-1}	0.38	0.55	0.88	0.0139	0.14

^{x,y}Within a row, means without a common superscript differ at $P < 0.10$.
[1]HL = haylage; CN = limit-fed corn; DDGS = limit-fed dried distillers grains.
[2]Collected before feeding.
[3]Collected 3 h postfeeding.
[4]Postfeeding concentration minus prefeeding concentration.
[5]GTT = glucose tolerance test.
[6]AUC = area under the curve.
[7]Initial insulin response = (2 + 5 min insulin concentration) – fasting insulin concentration.
[8]Ratio of insulin AUC/glucose AUC.

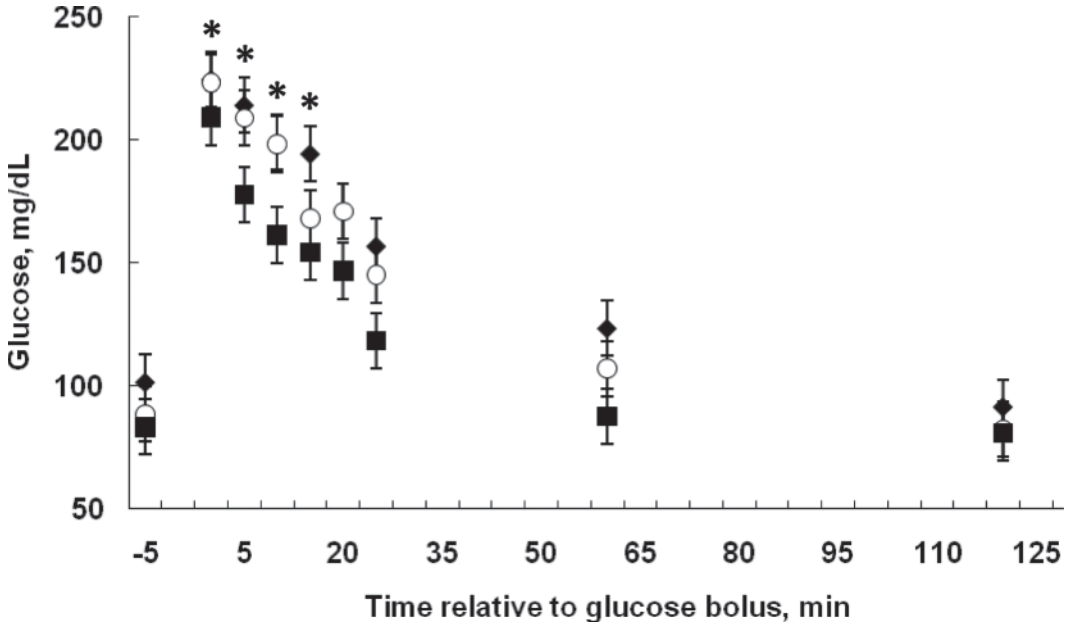

Figure 1. Plasma glucose concentration before and after glucose bolus infusion after 50 d on finishing diet in lambs from dams fed ad libitum haylage (◆), limit-fed corn (○), or limit-fed dried distiller grains (■) in late gestation. *Indicates a significant difference among treatments within minute ($P < 0.05$).

resistance of progeny at 1 yr of age (Gardner et al., 2005), whereas early- to mid-gestation maternal nutrient restriction resulted in hyperglycemia and decreased insulin secretion in lambs at 250 d of age (Ford et al., 2007). Lambs born from ewes with a greater BCS during gestation were also reported to have a greater initial insulin secretion in response to GTT (Cripps et al., 2008). Hyperinsulemia, during late gestation, has been associated with tissue specific insulin resistance of skeletal muscle, liver, and adipose tissue in fetus of sheep (Anderson et al., 2001a,b). In the present study, greater insulin concentrations and BCS were observed in ewes fed DDGS during gestation (Radunz et al., 2011), and their progeny tended to have a greater initial insulin secretion in response to a GTT. Together these studies suggest BCS and insulin resistance of dams during gestation could program the fetus to have similar response to high-energy diets fed postnatally.

In agreement with the present study, fed and fasted glucose concentrations under normal conditions were

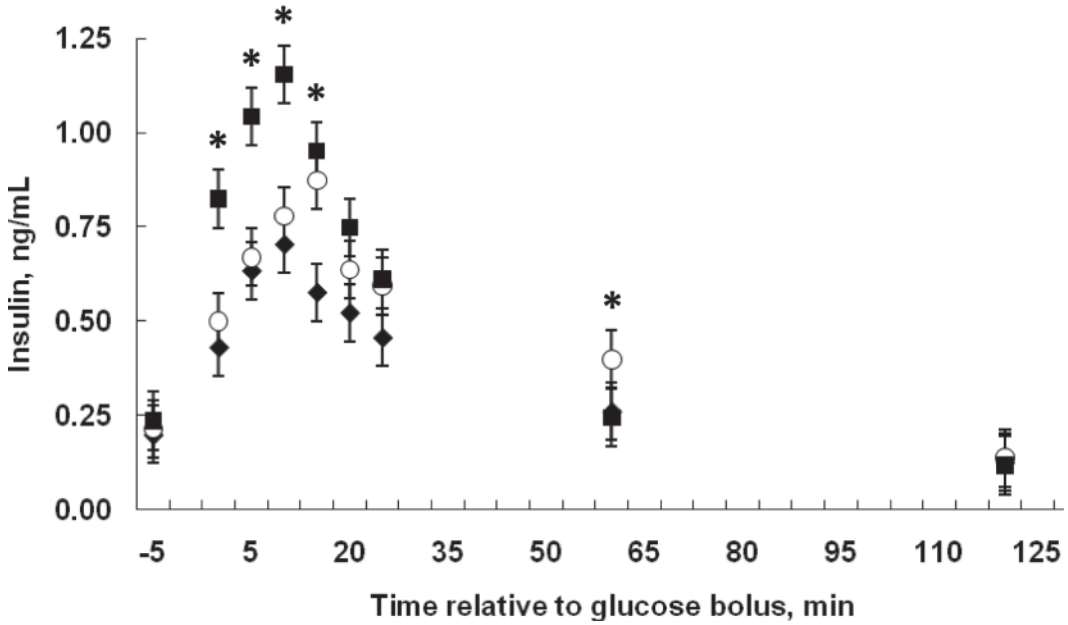

Figure 2. Plasma insulin concentration before and after glucose bolus infusion after 50 d on finishing diet in lambs from dams fed ad libitum haylage (◆), limit-fed corn (○), or limit-fed dried distiller grains (■) in late gestation. *Indicates a significant difference among treatments within minute ($P < 0.05$).

Table 4. Effects of prepartum dam diet on progeny carcass characteristics

	Treatment[1]				
Item	HL	CN	DDGS	SEM	*P*-value
Lambs (pens), n	36 (6)	33 (6)	27 (6)		
HCW, kg	26.0	28.5	28.2	1.93	0.16
Dressing percent	49.9[a]	50.1[a]	48.6[b]	0.44	0.04
12th-rib fat thickness, cm	0.67	0.66	0.70	0.038	0.61
Bodywall thickness, cm	2.05	2.12	2.14	0.274	0.96
LM area, cm^2	15.5[xy]	16.3[x]	14.6[y]	0.39	0.07
LM area, cm^2/kg of HCW	0.60[a]	0.58[ab]	0.53[b]	0.18	0.05
Internal fat, % of HCW					
Kidney and pelvic	1.94[y]	2.18[xy]	2.57[x]	0.131	0.06
Mesenteric	3.89	4.18	4.54	0.259	0.26
Total	5.95[y]	6.30[xy]	7.10[x]	0.251	0.06
USDA quality grade[2]					
Leg score	11.9[x]	11.5[xy]	10.7[y]	0.31	0.07
Confirmation score	11.9	11.7	11.5	0.14	0.19
Lean color score	12.3	12.3	12.2	0.15	0.88
Overall	12.2	11.9	11.7	0.12	0.12
BTRC,[3] %	49.5[a]	49.3[a]	48.6[b]	0.19	0.04
Organs					
Liver wt, kg	0.97	1.03	1.07	0.032	0.14
Kidney wt, g	137.8	137.0	150.4	8.15	0.40
Liver wt, % HCW	3.83	3.73	3.87	0.082	0.51
Kidney wt, % HCW	0.52	0.49	0.55	0.034	0.28
Intramuscular fat,[4] %	3.06	2.73	2.96	0.165	0.27
Slice shear force, kg	20.08	23.11	20.24	2.972	0.72

[a,b]Within a row, means without a common superscript differ at $P < 0.05$.
[x,y]Within a row, means without a common superscript differ at $P < 0.10$.
[1]HL = haylage; CN = limit-fed corn; DDGS = limit-fed dried distillers grains.
[2]Quality grade: 9 = Good$^+$, 10 = Choice$^-$, 11 = Choice, 12 = Choice$^+$, 13 = Prime$^-$ (USDA, 1992).
[3]BTRC = boneless trimmed retail cuts.
[4]Measured by ether extract of 2.54-cm chop posterior to 12th rib.

not associated with responses to glucose tolerance as measured by GTT (Gardner et al., 2005). In contrast, low birth weight lambs fed a high-energy diet postnatal had greater glucose and insulin concentrations, but this was attributed to a 20 to 45% greater feed intake during this time period (Greenwood et al., 2000). In the present study, changes in intake and glucose tolerance were small relative to the previous studies discussed.

Lamb Carcass Measurements

Hot carcass weight was similar ($P = 0.16$) among treatments, whereas dressing percents were greater ($P = 0.04$) in lambs from dams fed HL or CN than for lambs from ewes fed DDGS (Table 4). Internal fat weight tended to be greater ($P = 0.06$) for lambs from ewes fed DDGS than HL, and because this was removed before collection of HCW, this weight could have contributed to the reduced dressing percent observed. By experimental design, 12th-rib fat thickness was similar ($P = 0.6$) among treatments. Lambs from ewes fed DDGS had smaller LM area per kilogram of HCW than lambs from ewes fed HL, whereas lambs from ewes fed CN were intermediate ($P = 0.05$). Leg score followed a similar pattern as LM area, in which lambs from ewes fed HL tended to be greater than DDGS, with CN intermediate ($P = 0.07$). Proportion of KPH and overall internal fat tended to be greater ($P = 0.07$) for lambs from ewes fed DDGS than those from ewes fed HL, whereas kidney and liver weights were similar ($P \geq 0.14$) among treatments. Lambs from ewes fed DDGS had a decreased percentage ($P = 0.04$) of calculated boneless trimmed retail cuts than lambs from ewes fed CN or HL. These results suggest energy partitioning of muscle and fat in progeny could have been altered by maternal nutrition.

Maternal undernutrition during gestation has been associated with increased postnatal fat deposition, especially in the perirenal fat of progeny (Symonds et al., 1998; Gardner et al., 2005; Ford et al., 2007). Subcutaneous fat was also greater in lambs from those studies, but this is not comparable with the present study because our lambs were slaughtered at a similar subcutaneous fat thickness. In fetal sheep, 80% of fat deposited during gestation is located around the kidneys (Symonds et al., 2003) at parturition with most deposition occurring in the last few weeks of gestation (Gopalakrishnan et al., 2001). In sheep, increased insulin resistance has been associated with greater perirenal fat deposition (Gardner et al., 2005; Ford et al., 2007). Late gestation is a critical period of development of insulin signaling proteins downstream from insulin receptors in adipose

Table 5. Effects of prepartum dam dietary energy source on progeny wholesale lamb cuts

	Treatment[1]				
Item	HL	CN	DDGS	SEM	*P*-value
Lambs (pens), n	12 (6)	12 (6)	11 (6)		
HCW, kg	26.0	28.5	28.2	1.93	0.16
Total wt, kg					
Hindsaddle	12.6	13.4	13.0	0.58	0.55
Leg	4.2	4.5	4.4	0.19	0.43
Loin	1.6	1.4	1.4	0.15	0.66
Foresaddle	13.3	14.4	13.8	0.67	0.42
Rack	1.3	1.5	1.5	0.07	0.28
Shoulder	2.7	3.2	2.9	0.21	0.24
Percent HCW					
Hindsaddle	47.6	47.2	46.7	0.42	0.30
Leg	16.0	16.0	15.9	0.21	0.79
Loin	5.2	5.3	5.2	0.15	0.93
Foresaddle	51.0	51.7	50.4	0.66	0.44
Rack	4.9	4.9	5.0	0.19	0.95
Shoulder	10.1	10.8	9.7	0.21	0.33

[1]HL = haylage; CN = limit-fed corn; DDGS = limit-fed dried distillers grains.

tissue and may contribute to postnatal insulin resistance of offspring. Protein restriction in rats has led to downregulation of these proteins and hyperinsulemia of progeny (Fernandez-Twinn et al., 2005). These studies have not established a direct cause and effect between adipose deposition and insulin resistance, but the present study and previous studies demonstrate a relationship between fat deposition and insulin sensitivity that is associated with maternal nutrition during gestation.

In Radunz (2009) calves from dams fed HL or DDGS during late gestation had greater intramuscular fat content than those from dams fed CN, and in the present study, a similar numeric response occurred, but no differences were observed ($P = 0.27$). Insulin resistance has been associated with greater triglyceride storage within muscle (Lewis et al., 2002). Few studies have reported effects of maternal nutrition on intramuscular fat deposition of progeny, especially in sheep. In cattle, intramuscular adipose cells are more insulin sensitive than subcutaneous fat cells (Rhoades et al., 2007). That study would suggest greater insulin secretion on a high-concentrate diet could result in greater intramuscular fat deposition; however, the increased insulin secretion due to GTT in lambs from ewes fed DDGS did not result in a significantly greater intramuscular fat content in the present study. The small changes in insulin secretion in the current study may not have been great enough to increase fat deposition in intramuscular fat cells. Varied results in these studies could be reflective of differences in species (ovine vs. bovine), fetal number

Table 6. Effects of prepartum dam diet on progeny muscle weights and percentage of wholesale cuts

	Treatment[1]				
Item	HL	CN	DDGS	SEM	*P*-value
Lambs (pens), n	12 (6)	12 (6)	11 (6)		
Total muscle wt, kg	5.09	5.34	5.09	0.234	0.62
Leg	2.47	2.59	2.45	0.116	0.58
Loin	0.39	0.42	0.38	0.019	0.49
Rack	0.54	0.60	0.57	0.032	0.27
Shoulder	1.32	1.41	1.32	0.085	0.63
Total muscle, %	19.6	19.1	18.6	0.50	0.43
Leg	2.7	3.1	2.9	0.21	0.24
Loin	52.3^{x}	48.8^{xy}	43.7^{y}	2.17	0.10
Rack	42.5	44.1	41.7	1.63	0.56
Shoulder	50.6	49.3	50.4	1.65	0.82
Semitendinosus wt, kg	0.13	0.13	0.13	0.012	0.65
LM wt, kg	0.66	0.72	0.64	0.033	0.24
LM, % HCW	2.55	2.57	2.36	0.071	0.20

[x,y]Within a row, means without a common superscript differ at $P < 0.10$.
[1]HL = haylage; CN = limit-fed corn; DDGS = limit-fed dried distillers grains.

Table 7. Effects of prepartum dam diet on progeny fat weights

	Treatment[1]				
Item	HL	CN	DDGS	SEM	*P*-value
Lambs (pens), n	12 (6)	12 (6)	11 (6)		
Leg					
Total fat, kg	0.90	0.97	0.99	0.068	0.66
Subcutaneous fat, kg	0.67	0.72	0.76	0.061	0.57
Intermuscular fat, kg	0.20	0.20	0.17	0.017	0.48
Total fat, %	21.1	21.5	22.5	1.37	0.77
Subcutaneous fat, %	15.3	15.8	17.0	0.99	0.53
Intermuscular fat, %	4.6	4.4	4.0	0.48	0.48
Loin					
Total fat, kg	0.49	0.53	0.54	0.042	0.63
Subcutaneous fat, kg	0.33	0.36	0.38	0.031	0.50
Intermuscular fat, kg	0.16	0.17	0.16	0.015	0.86
Total fat, %	36.0	35.7	37.4	2.01	0.81
Subcutaneous fat, %	24.3	24.2	26.4	1.55	0.56
Intermuscular fat, %	11.7	11.3	11.0	0.83	0.84
Rack					
Total fat, kg	0.58	0.67	0.66	0.054	0.44
Subcutaneous fat, kg	0.45	0.50	0.49	0.038	0.57
Intermuscular fat, kg	0.20	0.21	0.20	0.018	0.85
Total fat, %	45.4	50.8	49.4	3.81	0.57
Subcutaneous fat, %	20.6	22.3	21.8	1.15	0.54
Intermuscular fat, %	19.8	21.1	20.4	1.84	0.85
Shoulder					
Total fat, kg	0.67	0.75	0.68	0.059	0.58
Subcutaneous fat, kg	0.29	0.33	0.28	0.043	0.69
Intermuscular fat, kg	0.36	0.40	0.39	0.033	0.64
Total fat, %	24.2	25.4	24.5	1.52	0.82
Subcutaneous fat, %	10.9	11.5	10.7	1.47	0.91
Intermuscular fat, %	13.5	14.2	14.2	0.98	0.82
Carcass					
Total fat wt, kg	2.46	2.70	2.78	0.19	0.46
Subcutaneous fat wt, kg	1.90	2.10	2.11	0.146	0.51
Intermuscular fat wt, kg	0.89	0.96	0.10	0.065	0.74
Total fat, %	9.4	9.7	10.3	0.54	0.55
Subcutaneous fat, %	75.7	76.0	73.7	2.18	0.73
Intermuscular fat, %	36.4	36.1	33.0	1.84	0.40

[1]HL = haylage; CN = limit-fed corn; DDGS = limit-fed dried distillers grains.

(twin vs. single), genetic variation (1 sire vs. 5 sires), and timing of maternal nutrition treatments (mid vs. late gestation).

Maternal prepartum diet resulted in no differences ($P \geq 0.12$) among treatments in quality grade measurements of conformation score, lean color score, and overall quality grade (Table 4). These are subjective measurements of muscle to lean conformation and quality factors such as lean color and flank streaking. In the current study, no change in quality grade was observed. Maternal diet prepartum resulted in only minor changes in carcass composition, which do not affect final quality grade determination.

Wholesale cuts were dissected into bone, muscle, and fat to determine if dam prepartum diet affected partitioning of nutrients to different tissues. Overall wholesale cut weights and proportions were similar among treatments ($P \geq 0.24$; Table 5). Proportion of muscle in loin tended ($P = 0.10$) to be greater with HL than DDGS with CN intermediate (Table 6). In contrast, muscle proportions of rack, shoulder, and leg were not different ($P \geq 0.24$) among treatments, nor was proportion of total LM. The small changes in muscle would not appear to have practical significance in food animal production, but reduced muscle proportion in lambs from ewes fed DDGS could indicate a change in programming of skeletal muscle during fetal development.

Skeletal muscle is the main consumer of fatty acids and glucose by the animal (Goodpaster and Wolf, 2004), and changes in muscle development during gestation could contribute to postnatal insulin resistance. Previous studies have observed maternal nutrient restriction during gestation has been associated with reduced birth weight, reduced proportion of muscle weight, an increase in type II (oxidative) muscle fibers, decreased GLUT 4 transporter, accumulation of triglycerides within muscle, and impaired mitochondrial function (Zhu et al., 2006; Costello et al., 2008). In addition to these observations, insulin concentrations were greater in maternal and fetal plasma due to overnutrition of ewes during late gestation (Zhu et al., 2008). Prolonged exposure to increased concentrations of insulin could

Table 8. Effects of prepartum dam diet on progeny bone weights and percentage of wholesale cuts

	Treatment[1]				
Item	HL	CN	DDGS	SEM	*P*-value
Lambs (pens), n	12 (6)	12 (6)	11 (6)		
Total bone wt, kg	1.76	1.92	1.86	0.091	0.41
Leg	0.70	0.76	0.75	0.046	0.57
Loin	0.21	0.21	0.24	0.017	0.41
Rack	0.26	0.27	0.26	0.016	0.84
Shoulder	0.59	0.65	0.59	0.042	0.41
Total bone, %	6.8	6.8	6.9	0.20	0.92
Leg	16.8	17.4	17.5	0.66	0.76
Loin	14.9	14.0	16.0	1.10	0.48
Rack	20.6	19.7	20.1	1.04	0.79
Shoulder	22.9	23.0	23.2	0.978	0.97
Femur wt, kg	0.22	0.23	0.23	0.010	0.65
Femur length, cm	18.7	18.9	18.8	0.26	0.81

[1]HL = haylage; CN = limit-fed corn; DDGS = limit-fed dried distillers grains.

predispose the fetus to insulin resistance, which is associated with decreased muscle mass and increased fat deposition. In the present study, muscle mass at birth was not affected by prepartum dam dietary energy source (Radunz et al., 2011); however, other muscle characteristics as discussed previously were not measured and warrant further investigation.

Subcutaneous and seam fat deposition in wholesale cuts were similar ($P \geq 0.40$) among treatments (Table 7). The experiment was designed to slaughter lambs at similar subcutaneous fat thickness, and these results would indicate this objective was achieved. Seam fat is the second largest fat depot in a lamb carcass; however, few studies have investigated deposition of seam fat relative to subcutaneous fat. Previous studies have indicated intramuscular fat may have different deposition patterns (Radunz, 2009) and insulin sensitivity (Rhoades et al., 2007) relative to subcutaneous fat deposition. The current study indicates seam fat was similar to subcutaneous fat deposition and is not altered by changes in maternal diet during gestation.

Dam prepartum diet did not affect ($P > 0.41$) bone weights or proportions (Table 8). When muscle and adipose tissue have been altered as a result of maternal nutrient restriction, this has not been associated with changes in proportion of bone mass (Ford et al., 2007) or ash content of fetal carcasses (Luther et al., 2007). Rate of bone growth was not different in light and heavy birth weights lambs (Greenwood et al., 1998), but light birth weight lambs had a decreased ash content at birth and 20 kg of BW. In the present study, lambs slaughtered at birth had similar bone mass (Radunz et al., 2011) and similar growth rate from birth to slaughter; therefore, bone growth and development does not appear to be affected by maternal diet in mid to late gestation when adequately fed.

In conclusion, mid- to late-gestation dam diet affected maternal plasma insulin concentration, which appears to be associated with progeny insulin sensitivity. Progeny insulin resistance was associated with alternations in fat deposition affecting primarily internal fat. The changes in carcass composition may have had small practical significance; however, they provide evidence that changes in maternal metabolism due to winter-feeding system may have long-term impacts on progeny growth and body composition. Further research is required to determine specific effects of maternal nutrition during gestation on fetal muscle and adipose tissue development and their long-term implications.

LITERATURE CITED

Anderson, M. S., J. Flowers-Ziegler, U. G. Das, W. W. Hay Jr., and S. U. Devaskar. 2001a. Glucose transporter protein responses to selective hyperglycemia or hyperinsulemia in fetal sheep. Am. J. Physiol. Regul. Integr. Comp. Physiol. 281:R1545–R1552.

Anderson, M. S., J. He, J. Flowers-Ziegler, S. U. Devaskar, and W. W. Hay Jr.. 2001b. Effects of selective hyperglycemia and hyperinsulinemia on glucose transporters in fetal ovine skeletal muscle. Am. J. Physiol. Regul. Integr. Comp. Physiol. 281:R1256–R1263.

Benson, J. A., and C. K. Reynolds. 2001. Effects of abomasal infusion of long-chain fatty acids on splanchnic metabolism of pancreatic and gut hormones in lactating dairy cows. J. Dairy Sci. 84:1488–1500.

Costello, P. M., A. Rowlerson, N. A. Astaman, F. E. W. Anthony, A. A. Sayer, C. Cooper, M. A. Hanson, and L. R. Green. 2008. Peri-implantation and late gestation maternal undernutrition differentially affect fetal sheep skeletal muscle development. J. Physiol. 586:2371–2379.

Cripps, R. L., L. R. Green, J. Thompson, M. S. Martin-Gronert, M. Monk, M. Sheldon, M. A. Hanson, C. N. Hales, and S. E. Ozanne. 2008. The effect of maternal body condition score before and during pregnancy on the glucose tolerance of adult sheep offspring. Reprod. Sci. 15:448–456.

Fernandez-Twinn, D. S., A. Wayman, S. Ekizoglou, M. S. Martin, C. N. Hales, and S. E. Ozanne. 2005. Maternal protein restriction leads to hyperinsulinemia and reduced insulin-signaling protein expression in 21-mo-old female rat offspring. Am. J. Physiol. Regul. Integr. Comp. Physiol. 288:R368–R373.

Ford, S. P., B. W. Hess, M. M. Schwope, M. J. Nijland, J. S. Gilbert, K. A. Vonnahme, W. J. Means, H. Han, and P. W. Nathanielsz. 2007. Maternal undernutrition during early to mid-gestation in

the ewe results in altered growth, adiposity, and glucose tolerance in male offspring. J. Anim. Sci. 85:1285–1294.
Gardner, D. S., K. Tingey, B. W. M. Van Bon, S. E. Ozanne, V. Wilson, J. Dandrea, D. H. Keisler, T. Stephenson, and M. E. Symonds. 2005. Programming of glucose-insulin metabolism in adult sheep after maternal undernutrition. Am. J. Physiol. Regul. Integr. Comp. Physiol. 289:R947–R954.
Godfrey, K. M., and D. J. P. Barker. 2001. Fetal programming and adult health. Public Health Nutr. 4:611–624.
Goodpaster, B. H., and D. Wolf. 2004. Skeletal muscle lipid accumulation in obesity, insulin resistance, and type 2 diabetes. Pediatr. Diabetes 5:219–226.
Gopalakrishnan, G., S. M. Rhind, T. Stephenson, C. E. Kyle, A. N. Brooks, M. T. Rae, and M. E. Symonds. 2001. Effect of maternal nutrient restriction at defined period in early to mid gestation on placento-fetal, kidney and adipose tissue weights at 110 day gestation in sheep. Early Num. Dev. 63:58–59.
Greenwood, P. L., A. S. Hunt, J. W. Hermanson, and A. W. Bell. 1998. Effects of birth weight and postnatal nutrition on neonatal sheep: I. Body growth and composition, and some aspects of energetic efficiency. J. Anim. Sci. 76:2354–2367.
Greenwood, P. L., A. S. Hunt, J. W. Hermanson, and A. W. Bell. 2000. Effects of birth weight and postnatal nutrition on neonatal sheep: II. Skeletal muscle growth and development. J. Anim. Sci. 78:50–61.
Huntington, G. B., C. K. Reynolds, and B. H. Stroud. 1989. Techniques for measuring blood flow in splanchnic tissues of cattle. J. Dairy Sci. 72:1583–1595.
Husted, S. M., M. O. Nielsen, M. P. Tyesen, A. Kiani, D. Blache, and K. L. Ingvartsen. 2007. Programming of intermediate metabolism in young lambs affected by late gestational maternal undernourishment. Am. J. Physiol. Endocrinol. Metab. 293:E548–E557.
Kaneko, J. J. 1989. Clinical Biochemistry of Domestic Animals. 4th ed. Acad. Press, San Diego, CA.
Leahy, J. L. 2005. Pathogensis of Type 2 diabetes mellitus. Arch. Med. Res. 36:197–209.
Lewis, G. F., A. Carpentier, K. Adehi, and A. Giaccca. 2002. Disordered fat storage and mobilization in the pathogenesis of insulin resistance and type 2 diabetes. Endocr. Rev. 23:201–229.
Luther, J., R. Aitken, J. Milne, M. Matsuzaki, L. Reynolds, D. Redmer, and J. Wallace. 2007. Maternal and fetal growth, body composition, endocrinology, and metabolic status in undernourished adolescent sheep. Biol. Reprod. 77:343–350.
NAMP. 1997. The Meat Buyers Guide. N. Am. Meat Proc. Assoc., Weimar, TX.
NRC. 1985. Nutrient Requirements of Sheep. 6th rev. ed. Natl. Acad. Press, Washington, DC.
Radunz, A. E. 2009. Effects of prepartum dam energy source on progeny growth, glucose tolerance, and carcass composition in beef and sheep. PhD Diss. The Ohio State University, Columbus.
Radunz, A. E., F. L. Fluharty, H. N. Zerby, and S. C. Loerch. 2011. Winter-feeding systems for gestating sheep I: Effects on pre- and postpartum ewe performance and lamb progeny preweaning performance. J. Anim. Sci. 89:467–477.
Rhoades, R. D., J. E. Sawyer, K. Y. Chung, M. L. Schell, D. K. Lunt, and S. B. Smith. 2007. Effects of dietary energy source on in vitro substrate utilization and insulin sensitivity of muscle and adipose tissues of Angus and Waygu steers. J. Anim. Sci. 85:1719–1726.
Shackelford, S. D., T. L. Wheeler, and M. Koohmaraie. 2004. Evaluation of sampling, cookery, and shear force protocols for objective evaluation of lamb longissimus tenderness. J. Anim. Sci. 82:802–807.
Soto, N., R. A. Bazaes, V. Pena, T. Salazar, A. Avila, G. Iniguez, K. K. Ong, D. B. Dunger, and M. V. Mericq. 2003. Insulin sensitivity and secretion are related to catch-up growth in small-for-gestational-age infants at age 1 year: Results from a prospective cohort. J. Clin. Endocrinol. Metab. 88:3645–3650.
Susin, I., S. C. Loerch, and K. E. McClure. 1995. Effects of feeding a high-grain diet at a restricted intake on lactation performance and rebreeding of ewes. J. Anim. Sci. 73:3199–3205.
Symonds, M. E., A. Mostyn, S. Pearce, H. Budge, and T. Stephenson. 2003. Endocrine and nutritional regulation of fetal adipose tissue development. J. Endocrinol. 179:293–299.
Symonds, M. E., I. D. Phillips, R. V. Anthony, J. A. Owens, and I. C. McMillen. 1998. Prolactin receptor gene expression and foetal adipose tissue. J. Neuroendocrinol. 10:885–890.
USDA. 1992. Official United States standards for grade of lamb, yearling mutton, and mutton carcasses. AMS, USDA, Washington, DC.
Wallace, J. M., J. S. Milne, and R. P. Aitken. 2005. The effect of overnourishing singleton-bearing adult ewes on nutrient partitioning to the gravid uterus. Br. J. Nutr. 94:533–539.
Zhu, M. J., S. P. Ford, W. J. Means, B. W. Hess, P. W. Nathanielsz, and M. Du. 2006. Maternal nutrient restriction affects properties of skeletal muscle in offspring. J. Physiol. 575:241–250.
Zhu, M. J., B. Han, J. Tong, C. Ma, J. M. Kmzey, K. R. Underwood, Y. Xiao, B. W. Hess, S. P. Ford, P. W. Nathanielsz, and M. Du. 2008. AMP-activated protein kinase signaling pathways are down regulated and skeletal muscle development impaired in fetuses of obese, over-nourished sheep. J. Physiol. 586:2651–2664.