Effects of timing of weaning on energy utilization in primiparous beef cows and post-weaning performance of their progeny[1]

Aksel Wiseman, Miles Redden, Adam McGee, Courtney Spencer, Ryan Reuter, Gerald Horn, and David Lalman[2]

Oklahoma State University, Department of Food and Animal Science, Stillwater, Oklahoma, 74078

Abstract: Early weaning is used to minimize cow nutrient requirements in situations where feed inputs are scarce or expensive. For many years, maintenance energy requirements have been assumed to be 20% greater in lactating compared with non-lactating beef cows. While not well established, maintenance energy requirements are thought to be greatest in primiparous cows and to decline with age. Consequently, early weaning primiparous cow–calf pairs should improve overall efficiency, particularly in situations where mid-to-late lactation forage or feed nutritive value is low. The objective of this study was to determine the biological efficiency of early weaning and maintenance energy requirements of lactating versus non-lactating primiparous cows. Experiments were conducted in two consecutive years using 90 primiparous cows and their calves (48 in yr 1, 42 in yr 2). Pairs were randomly assigned to one of the six pens (8 pairs/pen yr 1, 7 pairs/pen yr 2) and pens were randomly assigned to 1 of 2 treatments; (1) early weaning (130 d ± 15.4; EW, $n = 6$) and (2) traditional weaning (226 d ± 13.1; TW, $n = 6$). Late lactation cow and calf performance and feed consumption were measured for 92 d (yr 1) and 100 d (yr 2). Cows were limit-fed to meet maintenance requirements, while calves were offered ad libitum access to the same diet in a creep-feeding area. Calves were not allowed access to the cows' feed. Cow feed intake, body condition score, body weight (BW), milk yield and composition, and calf body weight gain and creep feed intake were recorded. After accounting for lactation and retained energy, there was a trend for greater maintenance energy requirements of lactating primiparous cows ($P = 0.07$). From the early weaning date to traditional weaning date, calf average daily gain (ADG) was greater ($P < 0.01$) for TW calves. Feed and energy efficiency of the pair was improved for the TW system ($P < 0.01$). Greater ADG were reported for EW calves during the stocker period ($P = 0.03$), but there were no differences during the finishing period ($P > 0.40$). At harvest, BW was greater ($P = 0.02$) and gain to feed ratio tended ($P = 0.06$) to be improved for TW calves. The increased TW calf performance offset the additional maintenance costs of their lactating dams, resulting in the TW system converting total feed energy to kilograms of calf BW gain more efficiently.

Key words: beef cows, nutrient requirements, post-weaning performance, primiparous cows, weaning system

© The Author(s) 2019. Published by Oxford University Press on behalf of the American Society of Animal Science. All rights reserved. For permissions, please e-mail: journals.permissions@oup.com.

J. Anim. Sci. 2019.97:1198–1211
doi: 10.1093/jas/skz019

INTRODUCTION

Reproductive success in a defined breeding season is the culmination of the interval from parturition to first ovulatory estrus, conception rate of cyclic cows, and early embryo survival through

---

[1] Funding for this work was provided by the Oklahoma Agricultural Experiment Station and the National Institute of Food and Agriculture and U.S. Department of Agriculture, under award numbers 2012–02355 and 2013-69002-23146.

[2] Corresponding author: david.lalman@okstate.edu

Received October 13, 2018.
Accepted January 15, 2019.

the first trimester (Banta et al., 2005). Longer postpartum interval in primiparous cows has been identified as the primary cause of reproductive failure when compared with multiparous cows (Wiltbank et al., 1964; Bellows and Short, 1978; Triplett et al., 1995). Negative energy balance after calving further extends the postpartum interval in primiparous cows (Houghton et al., 1990; Lalman et al., 1997). However, increasing postpartum energy intake may not be economically advantageous because additional energy supplied is partitioned to both milk and maternal tissue retained energy (Jenkins and Ferrell, 1992; Reynolds and Tyrrell, 2000). In turn, eliminating the nutrients required for milk production results in a 51–44% decrease in energy demands of the dam (Neville, 1974, Peterson et al., 1987). Consequently, early weaning has been used to reduce energy requirements, alleviate negative energy balance, and achieve maternal tissue gain when nutrient availability is limiting.

Several experiments have reported that lactation increases maintenance energy requirements (Moe et al., 1970; Patle and Mudgal, 1975, 1977; Ferrell and Jenkins, 1985). Therefore, early weaning should result in an additional reduction in cow maintenance cost (NASEM, 2016). The energy savings from reduced maintenance and termination of milk production could be redirected to calf growth as additional feed, thereby potentially enhancing production system efficiency. However, the use of early weaning for primiparous beef cows managed in drylot systems has not been studied. The objective of this study was to determine the biological effects of timing of weaning on energy utilization and production efficiency in primiparous beef cows and post-weaning performance of their progeny. The hypothesis was that maintenance energy requirements are greater in lactating primiparous females and, therefore, removing additional energy required for maintenance during lactation should improve efficiency of feed energy utilization.

MATERIALS AND METHODS

All procedures and protocols were approved by the Oklahoma State Animal Care and Use Committee (#AG-15–23). Performance experiments were conducted over 2 yr at the Range Cow Research Center near Stillwater, OK. Ninety fall calving Angus and Angus × Hereford primiparous cows [410 ± 38 kg initial body weight (BW)] and their Angus and Hereford sired calves (111 ± 16 kg initial BW) were used (48 in yr 1, 42 in yr 2). Additionally, an apparent total tract digestibility experiment was conducted using four lactating and four non-lactating 2- and 3-yr-old Angus and Hereford × Angus cows from the same herd.

Design, Facilities, and Management

Each year at the time of early weaning (day 0), cows were randomly assigned to six outdoor dry lot pens (8 cows/pen, year 1; 7 cows/pen, year 2) and pens were randomly assigned to either early weaning (EW, $n = 6$; 130 ± 15.4 d) or traditional weaning (TW, $n = 6$; 226 ± 13.1 d). Three additional dry lot pens were used each year to house calves assigned to the EW treatment while calves assigned to the TW treatment remained with their dams. The 226-d weaning age for TW was selected due to traditionally later weaning age commonly used in Southern Great Plains fall calving systems compared to approximate 205-d weaning age used in spring calving systems (Hudson et al., 2010).

Early weaned pairs were not allowed fence-line access to eliminate the possibility of suckling. Each pen was equipped with fence-line feed bunks and water tanks to provide ad libitum access to water. Pens for TW cow/calf pairs and EW cows provided approximately 103 m^2 of pen space per cow–calf pair and 1.03 linear meters of bunk space per cow. A separate creep area provided 0.34 linear meters of bunk space per calf. Approximately 35 m^2 of pen space per calf and 0.34 linear meters of bunk space per calf were available to calves assigned to the EW treatment. Pens were equipped with a minimum of 1.50 linear meters of windbreak on the north perimeter. Replicate groups of cows (EW) and cow–calf pairs (TW) were rotated through the six larger pens, with each replicate group shifting one pen in a clockwise direction every 28 d.

To minimize risk of acidosis an acclimation period of 10 d was used both years (day −10 to 0). For the first 5 d, pairs were allowed to graze dormant native pasture, while being supplemented with the experimental ration. The following 5 d, pairs were brought into the experimental pens daily and fed in the bunks used throughout the trial, then returned to graze. The same formulation of a total mixed ration was fed both years (Table 1). In year 1, a coccidiostat (Deccox, Zoetis Services, LLC, Florham Park, NJ) was added to the TMR at 100 mg/d for prevention of coccidiosis in calves. In year 2, an equal amount of Deccox was top-dressed over the ration in a cracked corn-based supplement provided at the rate of 0.454 kg/d. Equations from NASEM (2016) were used to estimate the initial amount of feed required to achieve

Table 1. Ingredient and chemical composition of diets fed to cows and calves during the drylot and apparent digestibility experiments

	Drylot[1] Yr 1	Drylot[1] Yr 2	Apparent Digestibility[1]
Ingredient, % dry matter			
Bermudagrass hay, chopped	33.3	33.3	33.3
Dried distiller's grains w/solubles	32.3	32.3	32.3
Rolled corn	24.1	24.1	24.1
Soybean meal, 47.5% crude protein	2.6	2.6	2.6
Limestone	2.1	2.1	2.1
Liquid supplement[3]	5.1	5.1	5.1
Chemical composition, dry matter basis			
CP, %[4]	17.7	17.8	19.1
NDF, %[4]	36.9	39.8	32.4
ADF, %[4]	20.6	21.8	16.0
Ash, %	7.0	8.4	8.6
TDN[5], %	74.1	66.5	73.7
DE[6], Mcal/kg	3.3	2.9	3.3
ME[7], Mcal/kg	2.7	2.4	2.7

[1] Drylot = diets fed to cows and calves during the experimental drylot period conducted between the early and conventional weaning times (day 0 to 96).

[2] Apparent digestibility = diets fed to cows and calves during the apparent total tract digestibility experiment.

[3] Liquid supplement contained 60% DM, 15% CP, 2.0% NaCl, 0.84% P, 0.57% Mg, 416 ppm Cu, 70,500 IU Vitamin A, (as-fed basis).

[4] CP = crude protein; NDF = neutral detergent fiber; ADF = acid detergent fiber.

[5] TDN = total digestible nutrients. Values for year 1 and 2 determined from measured chemical composition and summative equation using 48-h NDF in vitro digestibility (NRC, 2001). Digestibility study TDN determined using gross energy (GE) digestibility.

[6] DE = digestible energy. For year 1 and 2 determined as TDN (% DM)/100 × 4.409 (NASEM, 2016). Digestibility study DE determined as (daily GE – daily fecal energy)/kg of DMI.

[7] ME = Metabolizable energy. Values determined as DE × 0.82 (NASEM, 2016)

0.3 kg daily body weight (BW) gain in lactating and non-lactating primiparous cows [206 kcal ME (kg $BW^{0.75}$)$^{-1}$ d^{-1} for TW; 129 kcal ME (kg $BW^{0.75}$)$^{-1}$ d^{-1} for EW]. Feed delivered daily to each pen was adjusted weekly as needed to maintain BW gain of approximately 0.3 kg/d. Slight BW gain was desired to accommodate for additional growth of primiparous dams as they reach maturity.

Feed was offered daily at approximately 0700 hours. To differentiate between cow and calf feed consumption in the TW treatment, calves were penned each day prior to feeding. Cows consumed their feed in approximately 1 h. After cows consumed their feed, calves were returned to the pen where they had ad libitum access to a creep area containing the same diet as the cows (Table 1). Calves assigned to the EW treatment were provided access to the same diet (Table 1). Calf feed for both treatment groups was adjusted weekly in year 1 and daily in year 2 to achieve ad libitum feed intake. Calf feed refusals from the creep areas (TW) and feed bunks (EW) were collected and weighed each day. Daily samples were composited weekly within each pen and dried for 72 h at 50 °C.

On day −14 of each year, calves were administered a respiratory vaccine (Titanium 5, Elanco Animal Health, Greenfield, IN), a clostridial vaccine (Vision 7, Merck Animal Health, Madison, NJ), and oral anthelmintic (Safeguard, Merck Animal Health, Madison, NJ). Cows were also administered the oral anthelmintic on day −14. Amprolium solution (Corid, Merial Limited, Duluth, GA) was added to drinking water to provide 10 mg amprolium/kg BW for 5 d (day 9–13, yr 1; day 11–15, yr 2) to prevent coccidiosis. Prior to the experiment, cows were synchronized for timed artificial insemination (TAI) using a Co-Synch protocol (Stein et al., 2015). A controlled internal drug release (CIDR; Zoetis, Inc., Parsippany, NJ) device was inserted into the vagina and 100 mg gonadorelin hydrochloride (GnRH; Factrel, Zoetis Inc., Parsippany, NJ) was administered intramuscularly. Seven days later, the CIDR was removed and 25 mg prostaglandin F2α (Lutalyse; dinoprost tromethamine, Zoetis Inc., Parsippany, NJ) was administered intramuscularly. Sixty hours later, TAI was performed and a GnRH injection was administered to induce ovulation on cows that were non-responsive to the previous protocol. Following TAI, cows were exposed to fertile bulls for 43 d. Bulls were removed as pairs were transferred to the experimental pens. Cows were then observed morning and night for standing heat for the following 20 d. When estrus was observed, the cow was artificially inseminated approximately 12 h after the conclusion of estrous.

Milk Yield and Composition

Milk yield of cows assigned to the TW treatment was initially measured on day 35 and 20 of the experiment in yr 1 and 2, respectively, and at 28-d intervals thereafter. The procedure described by Marston et al. (1992) was used with the following modifications. A milking machine (Portable Vacuum Systems, Springville, UT) was utilized for complete evacuation. Cows and calves were separated twice to allow for standardization of milk production across all dams. On the day before milking, calves were removed from their dams at 1400 hours. Calves were not allowed access to creep feed during this period. At 2000 hours, calves were returned to their dams and were allowed to suckle until satiated. At the conclusion of the suckling period (2045 hours), calves were again removed from their dams. Milking began the next morning at 0500 hours allowing for an average 8-h separation. Cows were comingled in one pen and milked in random order. Cows were sent to one of the two working chutes, allowing for two cows to be milked simultaneously. After entering the chute, cows were intramuscularly injected with 1 mL of oxytocin (Oxoject, Henry Schein Animal Health, Dublin, OH) to assist with milk let down. Teats were then washed with warm, soapy water, dipped with an antibacterial solution, wiped dry, and hand stripped before attaching the milking claw. The milking claw remained attached until flow ceased. After removal of the milking claw, teats were hand stripped, to ensure complete evacuation, and then dipped with the antibacterial solution. Cows were then reunited with their calves and returned to their home pen. Any milk obtained from hand stripping was combined with the milk machine sample and weighed on a calibrated platform scale (Defender 5000, Ohaus Corp., Parsippany, NJ) to determine the total yield. In order to analyze milk composition, a subsample was taken in a vial containing 2-bromo-2-nitropropane-1,3-diol for preservation and shipped to the Heart of America Dairy Herd Improvement Association laboratory (Manhattan, KS). Milk energy content was estimated using the following equation (Eq. 13–46, NASEM, 2016):

$$E = (0.092 \times \text{MkFat}) + (0.049 \times \text{MkSNF}) - 0.0569$$

where E indicates energy content of milk (Mcal/kg), MkFat milk fat content (%), and MkSNF indicates milk solids not fat content (%). To adjust for differences in separation time, initiation and conclusion of milking were recorded. Milk yield was multiplied by the regression coefficient of yield on conclusion time to adjust all yields to an 8-h separation time. The 8-h yield was then multiplied by 3 to determine 24-h milk yield.

Maintenance Requirements

Feed intake required to maintain similar BW and body condition score (BCS; 1–9 scale) change served as the basis for energy balance and calculation of maintenance energy requirements. Initial feed total digestible nutrients (TDN) and metabolizable energy (ME) concentration at maintenance feeding level was determined each year using average chemical composition, the summative equation for TDN (NRC, 2001) and in vitro neutral detergent fiber (NDF) digestibility (Weiss et al., 1992). However, because different feeding levels were required to achieve desired modest BW gain in lactating and non-lactating cows, the apparent total tract digestibility trial was conducted after the performance experiment was completed. This sequence was necessary to conduct the apparent total tract digestibility study using the same feeding level as that used in the dry lot performance experiment. Subsequently, diet energy values for both years of the performance study were adjusted to an in vivo basis. This was accomplished by determining the ratio of summative equation-derived energy value for the digestibility experiment to the in vivo-derived gross energy (GE) digestibility of the same feed. Both year's summative equation-derived energy values from the performance experiments were multiplied by this ratio to determine in vivo adjusted TDN concentration. Finally, TDN was converted to DE, ME and net energy for maintenance (NEm) according to NASEM (2016) and Galyean et al., 2016.

Maintenance energy requirements were determined as

$$\text{MER} = (\text{MEI} - \text{MkE} - \text{TE}) \times (\text{MBW}^{-1}\ \text{d}^{-1})$$

where MER is maintenance energy requirements, MEI metabolizable energy intake, MkE milk energy, and TE indicates tissue energy. Milk energy was calculated using the equation from NASEM (2016) as described previously.

Each year, BW measurements were recorded at the initiation of the experiment (day 0) and weekly thereafter throughout the dry lot experimental phase (day 96). Weights were recorded early in the morning prior to feeding, and thus represented shrunk BW because cows had not been fed for 20 to 23 h prior to weighing. Cows and calves had access to water at all times. The definition for shrunk BW is ad libitum access to water and 18 h without food (NASEM, 2016). Maternal tissue retained energy was determined as

$$\mathrm{RE} = \mathrm{TBE}_{\mathrm{F}} - \mathrm{TBE}_{\mathrm{I}}$$

where RE is retained energy, $\mathrm{TBE}_{\mathrm{F}}$ total body energy on day 92 year 1, day 100 year 2, and $\mathrm{TBE}_{\mathrm{I}}$ is total body energy on day 0. Total body energy was calculated using Eq. 13-1, 13-2, 13-7, 13-8, 13-9, and 13-10 from NASEM (2016).

Apparent Total Tract Diet Digestibility

Apparent total tract diet digestibility was determined in a separate experiment using four lactating and four non-lactating 2- and 3-yr-old Angus and Hereford × Angus cows from the same herd. Beginning 45 d prior to the collection period, cows had ad libitum access to unprocessed grass hay (6.4% CP, 59% TDN), were fed 1 kg/d of a protein supplement (32% CP, DM basis), and 2 kg/d of the diet (chemical composition shown in Table 1). On day −40 the mixed ration feeding rate was increased by 1 kg/d, protein supplement was discontinued, and hay feeding rate was reduced by 2 kg per day. Hay and mixed ration feeding rate were adjusted similarly every 5 d until unprocessed grass hay was completely removed from the diet and the desired mixed ration feeding rate was achieved. Beginning day −5 and throughout the collection period, cows were housed in 2.4-m × 3.7-m individual pens with rubber mat flooring and fed at the same g/kg of $\mathrm{BW}^{0.75}$ rate as the cattle from the performance experiment and provided ad libitum access to water. Lactating cows were housed next to their calves with fenceline exposure and calves were turned in with their dam to nurse at 0700, 1300, and 2000 hours each day. The diet was sampled at 0700 hours daily. Total fecal collection was performed on day 5 to 9 at 0700 and 1900 hours. Morning and evening collections were thoroughly mixed prior to sampling, and subsamples equaling 5% of the total sample were taken from both collection times. The subsamples were dried in a forced air oven for 72 h (60 °C), ground through a 1 mm screen (Wiley Mill, Thomas Scientific, Swedesboro, NJ) and equal daily aliquots were pooled within cow. Pooled samples were analyzed for GE, fat, ADF, NDF, and ash content. Gross energy was determined for feed and feces via bomb calorimetry (Dairy One Forage Laboratory, Ithaca, NY). Fat content was determined utilizing the ether extract method (AOAC, 2012.) The acid detergent fiber (ADF) and NDF content were determined using Van Soest (1963) and Van Soest et al. (1991). Samples were ashed in a muffle furnace at 500 °C for 8 h to determine organic matter (OM) and ash concentrations. Digestibility components (GE, OM, NDF, ADF, and fat) were determined as

$$\text{Component digestibility} = \frac{\mathrm{CC}_{\mathrm{Feed}} - \mathrm{CC}_{\mathrm{Fecal}}}{\mathrm{CC}_{\mathrm{Feed}}} \times 100$$

where $\mathrm{CC}_{\mathrm{Feed}}$ is the concentration of the component in the feed and $\mathrm{CC}_{\mathrm{Fecal}}$ is the concentration of the component in the collected fecal matter.

Post-Weaning Calf Performance

Each year, after the conclusion of the dry-lot period (day 96), calves were weaned, comingled, and allowed to graze warm season perennial pasture [dominant forage species = Indian grass (*Sorghastrum nutans*), little bluestem (*Schizachyrium scoparium*), and switch grass (*Panicum virgatum*)] from late April to early August for 122 d. Weights were recorded on day 220 and day 216 in year 1 and 2, respectively. Immediately after calves assigned to the TW treatment were weaned, calves assigned to both treatments were provided 0.454 kg/d of a 38% (DM) CP supplement consisting primarily of cottonseed meal and wheat middlings. Monensin was included in the supplement at the rate of 150 mg/kg of supplement.

During August (day 220, $n = 27$ in yr 1; d 216, $n = 21$ in yr 2), steer calves were shipped to a commercial feedlot for finishing. Steers were separated into their original replicate groups from the initial 96-d dry lot study and assigned to pens accordingly (3 pens trt^{-1} yr^{-1}). A high-concentrate diet was fed with feed provided on an ad libitum basis throughout the finishing period. Upon arrival at the feeding facility, steers were allowed 16 h rest prior to processing, then administered a modified-live (Vista Once, Merck Animal Health, Madison, NJ) and clostridial vaccine (Vision 7, Merck Animal Health, Madison, NJ), as well as implanted with a combination trenbolone acetate and estradiol implant (Revalor-S, Merck Animal Health, Madison, NJ). Steers were then reimplanted with a combination trenbolone acetate and estradiol implant (Revalor-IS, Merck Animal Health, Madison, NJ) approximately 90 d later. Cattle were fed for 161 and 176 d and were therefore harvested 381 and 392 d after the initiation of the experiment in year 1 and 2, respectively.

Statistical Analysis

Data collected for cow performance and maintenance, digestibility and feed efficiency, and calf performance through the stocker phase were analyzed using the GLIMMIX procedure in SAS v. 9.4 as a one factor completely randomized design with pen as the experimental unit (SAS Institute Inc., Cary, NC). The model included treatment as a fixed effect and year as a random effect. Milk yield and composition were analyzed as a repeated measure using the autoregressive covariance structure to determine the effect of time (month) on milk yield and composition under the TW treatment, with individual cow serving as experimental unit. Significance was declared at $P < 0.05$. Initial calf weight differed in year 1 ($P < 0.01$). Consequently, the model for data collected on all phases of calf performance included initial BW as a covariate. Carcass grade and quality were analyzed using a binomial model. Where the model $P \leq 0.10$, treatment means were separated using least square means and reported using $\alpha \leq 0.05$.

RESULTS AND DISCUSSION

Similar BW and BCS change were achieved when EW cows were provided 66% of the feed (kg DM/d) provided to TW cows (Table 2). As intended, there were no differences due to treatment in cow BW ($P \leq 0.75$) or BCS ($P \leq 0.25$) throughout the experiment. Because these were immature primiparous 2-yr-old cows, feeding rate was adjusted weekly or bi-weekly to achieve modest maternal tissue gain. This objective was achieved for both treatment groups as cow BW and BCS increased during the experimental period. This feeding level resulted in approximately 1.38 and 2.1 times the amount of feed required to maintain zero BW or BCS change in non-pregnant, non-lactating primiparous cows. There was no difference in pregnancy rate ($P = 0.18$) between the two treatments. The primary objective of this experiment was to study the efficiency of feed energy use for calf pre- and post-weaning growth rather than dam reproductive efficiency. However, numerical differences in pregnancy rate when calves were weaned near the end of the breeding season in the current experiment, and improved pregnancy rate from previous research (Lusby et al., 1981) when calves were weaned prior to the breeding season, suggest a need to further investigate potential reproductive benefits.

Diet Digestibility and Feed Energy Concentration

Results of the apparent total tract digestibility experiment are shown in Table 3. Treatment groups were fed at the same g/kg $BW^{0.75}$ required

Table 2. Effects of timing of weaning on feed intake, body weight, body condition score, and pregnancy rate in limit-fed primiparous beef cows

	Treatment[1]			
Item	TW	EW	SEM	*P*-Value
Feed intake (dry matter basis) g/kg body weight$^{0.75}$	80.5	52.9	—	—
Cow body weight, kg				
January (day 0)	417	414	65	0.75
March (day 56)	429	428	14	0.95
April (day 96)	445	445	12	0.98
Cow BCS[2]				
January (day 0)	4.7	4.7	0.09	0.82
March (day 56)	5.0	5.0	0.09	0.84
April (day 96)	5.1	5.2	0.13	0.25
Pregnancy rate, %[3]	68.9	82.2	6.90	0.18

[1] TW = traditional weaning (226 d), EW = early weaning (130 d); *n* = 6 pens per treatment. Cows from each treatment were fed to achieve similar weight gain.

[2] Body Condition Score on a 1(emaciated) to 9 (obese) scale.

[3] Cows were synchronized and timed artificial insemination was performed on day −45. Subsequently, cows were exposed to fertile bulls for 43 d. Bulls were removed on day 0. Pregnancy was determined via rectal palpation approximately 100 d after the early EW date.

Table 3. Effects of lactation status and feed intake on diet apparent total tract digestibility in limit-fed 2- and 3-yr-old beef cows

	Treatment[1]			
Item	TW	EW	SEM	*P*-value
Dry matter intake, kg	7.6	5.0	0.21	< 0.01
OM digestibility, %[2]	72.7	73.1	2.03	0.85
GE digestibility, %[2]	74.1	73.3	2.81	0.79
NDF digestibility, %[2]	60.0	61.5	4.21	0.60
ADF digestibility, %[2]	57.7	61.9	5.11	0.51
Fat digestibility, %[3]	89.4	89.4	1.17	0.99

[1] TW = traditional weaning (226 d), EW = early weaning (130 d); $n = 4$ animals per treatment. The cow feeding rate was 81 g/kg $BW^{0.75}$ (TW) and 53 g/kg $BW^{0.75}$ similar to the drylot performance experiment.

[2] OM = organic matter (AOAC 2012); GE = gross energy via bomb calorimetry; NDF = neutral detergent fiber (Van Soest et al., 1991); ADF = acid detergent fiber (Van Soest et al., 1991).

[3] Fat digestibility determined via either extract method according to AOAC (2012).

to maintain similar BW change among treatment groups in the performance experiment. There was no difference in OM, GE, NDF, ADF, or fat digestibility between lactating and non-lactating cows ($P \geq 0.51$). These results are in contrast with other experiments where increased feed intake of diets with similar energy concentration was associated with reduced diet digestibility (Moe et al., 1965, Tyrrell and Moe, 1975, Trubenbach et al., 2016). Moe et al. (1965) reported a linear decline in TDN with increasing level of feed intake in lactating dairy cows consuming one to five times their maintenance requirement. Tyrrell and Moe (1975) also indicated that the TDN of a TMR declined at an increasing rate as the amount of TMR provided is increased in lactating cows. Early et al. (2016) reported no difference in diet digestibility when gestating beef cows were limit-fed 2 kg of wheat straw and fed increasing levels of concentrate resulting in DMI levels ranging from approximately 47 to 69 g/kg $BW^{0.75}$. In the current experiment, feeding level was manipulated to achieve modest BW gain in lactating cows and it is possible that the required feeding rate (80 g/kg $BW^{0.75}$) was low enough to avoid digestibility depression. However, Trubenbach et al. (2016) fed wheat straw, corn-based diets with energy concentrations similar to this experiment, and documented depressed digestibility with increasing feed intake from maintenance level up to approximately 69 g/kg $BW^{0.75}$. More work is required to elucidate diet, animal, and feeding management factors that influence energy availability in limit-fed beef cows. Similarly, in vivo total tract GE digestibility was not different between treatments (Table 3; $P = 0.79$) and averaged 73.7%. Parenthetically, this value is 3.7 percentage units less than summative equation-derived TDN determined for feed samples collected during this in vivo experiment (77.4%, data not shown). As described previously, this difference was used to adjust the diet energy value of the performance experiment to an in vivo basis.

Milk Production and Composition

Mean milk yield, milk fat and milk protein concentration measured in this experiment are similar to previous reports using primiparous cows fed to maintain or achieve moderate positive energy balance (Mondragon et al., 1983; Lalman et al., 2000). Mean milk yield was greater in February and March compared with January (Table 4; $P < 0.01$). Milk protein and solids non-fat concentrations were greater ($P < 0.01$) in February and March, respectively, compared with January, suggesting increased nutrients available for partitioning to milk components later during the restricted feeding period. Freetly et al. (2008) described an acute decline in heat production that occurs within 7 d of feed restriction. These authors also reported that after the acute phase of adaptation, heat production declined at a gradual rate for extended periods (Freetly et al., 2008). This pattern of adaptation could explain increased net energy partitioned to milk production after the first 30 d of feed restriction in the current experiment.

Maintenance Energy Requirements

Non-lactating primiparous cows required 66% of the MEI consumed by lactating primiparous cows (Table 5) to maintain similar BW and BCS. Maintenance energy requirements were calculated using equations from two different systems (Garrett, 1980; Galyean et al., 2016) and results are shown in Table 5. After subtracting energy used for milk production and maternal tissue gain, there

Table 4. Milk yield and milk composition in limit-fed primiparous beef cows during mid- and late-lactation

Item	January (day 27)	February (day 55)	March (day 83)	SEM	*P*-value
Milk yield, kg/d[1]	5.70^{a}	7.02^{b}	6.85^{b}	0.26	0.01
Milk energy, Mcal/kg[2]	0.68	0.69	0.71	0.01	0.12
Milk fat, %[3]	3.15	3.22	3.33	0.10	0.72
Milk protein, %[1,3]	2.93^{a}	3.05^{b}	$3.01^{a,b}$	0.05	< 0.01
Milk lactose, %[3]	5.01	4.96	4.97	0.02	0.98
Milk SNF, %[1,3,4]	9.13^{a}	$9.24^{a,b}$	9.37^{b}	0.09	< 0.01
MUN, %[1,3,4]	17.5^{b}	15.4^{a}	$16.3^{a,b}$	0.56	0.54

[1] Means with differing superscript differ $P < 0.05$.

[2] Milk energy production (Mcal NE_m), calculated using NASEM 2016 Eq. 13–46: (0.092 × % Fat) + (0.049 × % SNF) – 0.0569.

[3] Milk chemical component analyses conducted by Heart of America Dairy Herd Improvement Association Laboratory (Manhattan, KS).

[4] SNF = solids non-fat, MUN = milk urea nitrogen.

Table 5. Effects of timing of weaning on maintenance energy requirements in drylot, limit-fed lactating (TW) and non-lactating (EW) primiparous beef cows

	Treatment[1]			
Item	TW	EW	SEM	*P*-Value
ME intake, Mcal/d[2]	19.9	13.1	0.15	< 0.01
Milk energy, Mcal ME/d[3]	6.8	0	—	—
Tissue retained energy, Mcal ME/d	2.7	3.4	0.97	0.02
Garrett, 1980[4]				
Maintenance energy, Kcal ME/kg body weight$^{0.75}$	106.9	101.5	4.6	0.10
Maintenance energy, Kcal NE_m/kg body weight$^{0.75}$	68.9	65.5	1.8	0.11
Galyean et al., 2016[5]				
Maintenance energy, Kcal ME/kg body weight$^{0.75}$	112.6	106.9	4.2	0.11
Maintenance energy, Kcal NE_m/kg body weight$^{0.75}$	68.9	65.5	1.8	0.11

[1] TW = traditional weaning (226 d), EW = early weaning (130 d); n = 6 pens per treatment. Cows from each treatment were fed to achieve similar weight gain and calves were provided creep feed ad libitum.

[2] ME = metabolizable energy; Mcal = megacalorie; NE_m = Net energy for maintenance.

[3] Milk and tissue retained energy was converted to ME basis using equations of Garrett, 1980.

[4] $ME = DE \times 0.82$ and $NE_m = 1.37\,ME - 0.138\,ME^2 + 0.0105\,ME^3 - 1.12$.

[5] $ME = 0.9611 \times DE - 0.2999$ and $NE_m = 1.1104\,ME - 0.0946\,ME^2 + 0.0065\,ME^3 - 0.7783$.

was a tendency ($P = 0.10$) for approximately 5% greater ME required for maintenance in lactating cows using the Garrett (1980) equations. When NE_M requirements for maintenance were calculated using the Garret equations, a similar percentage difference was estimated, although these differences were not significant ($P = 0.11$). The Galyean et al. (2016) equations produced the same NE_M estimates required for maintenance as the Garrett, (1980) equations. The tendency for 5% greater ME requirements for maintenance in lactating cows is lower than previous reports, although this finding is consistent with literature suggesting that maintenance requirements are elevated in lactating beef cows (NASEM, 2016). Using in vivo apparent total tract digestibility and respiration calorimetry, Reynolds and Tyrrell (2000) estimated 29% greater maintenance energy requirements in lactating primiparous beef cows compared with non-lactating cows. In their work, daily feed consumption for non-lactating cows was about 67% that of lactating cows, resulting in 4.5 percentage units higher DM digestibility in non-lactating cows. Using similar techniques, Moe et al. (1970) reported a 22% increase in maintenance energy requirement of lactating Holstein and Jersey cows.

Compared with non-lactating Hereford cows, Neville and McCullough (1969) and Neville (1974) reported an increase in maintenance energy requirements for lactating cows of 30 and 38%, respectively. In the case of Neville (1974), sheep were used to determine in vivo diet digestibility at one level of feed intake and MEI was calculated using a constant of 3.62 Mcal ME per kg of TDN. In the case of Neville and McCullough (1969), MEI was calculated at one level of feed intake using equations relating chemical composition of forages to TDN and tabular TDN values for concentrate feeds were used. Similarly, Montaño-Bermudez et al. (1990) reported a range of 10 to 27% increase in maintenance energy requirements for lactating cows using a constant diet ME value. Ferrell and Jenkins (1985) reported a 16% increase in maintenance energy requirements for pregnant, lactating Angus × Hereford dams compared with non-pregnant, non-lactating Angus × Hereford dams by comparing several previous studies. In the work of Ferrell and Jenkins (1985), metabolizable energy intake was calculated using tabular values similar to the procedure of Neville and McCullough (1969).

Freetly et al., (2006a) documented increased heat production with increased retained energy and increased feed intake. Therefore, some of the differences in MER previously reported for lactating versus non-lactating cows could be a result of the higher feeding level required to maintain lactating cows, and these differences would be magnified in high-producing cattle. In the current experiment, differences in digestibility were not observed due to feed intake level/stage of production. However, in numerous published reports (Neville and McCullough, 1969; Neville, 1974; Ferrell and Jenkins, 1985; Montaño-Bermudez et al., 1990), diet digestibility was not measured directly and a single energy value was used for both lactating and non-lactating cows. In situations where increased feed intake of lactating cows results in reduced dietary energy concentration, the difference in MER between lactating and non-lactating cows would be overestimated.

The estimate of 65 kcal NEm/kg SBW$^{0.75}$ for non-lactating Angus and Hereford × Angus primiparous cows from the current study compares to 77 recommended for Angus and Hereford cattle (NASEM, 2016). Perhaps the low estimate of MER in these cows can be partially attributed to limit-feeding a relatively high-energy diet (Freetly et al., 2006b; Trubenbach et al., 2016). Similarly, the estimated MER for lactating primiparous cows (68.9 kcal/kg SBW$^{0.75}$) was substantially lower than suggested MER for crossbred Hereford × Angus (84.7 kcal/kg SBW$^{0.75}$) or Angus (92.4 kcal/kg SBW$^{0.75}$) cattle (NASEM, 2016).

Calf Drylot Performance

Both TW and EW calves had ad libitum access to the same diet as their dams during the drylot performance study. Voluntary feed intake was 17.5% greater for EW calves ($P < 0.01$, Table 6) compared with TW calves still nursing their dams. However, the sum of feed and milk energy intake for TW calves was 36.5% greater compared with feed energy intake alone in EW calves ($P < 0.01$). As a result, TW calves had greater ADG ($P < 0.01$) and total BW gain ($P < 0.03$). A review of the literature reveals mixed results for calf performance when early weaning management is compared with more traditional weaning age. Arthington and Kalmbacher (2003) found contrasting results with EW calves offered supplemental grain on ryegrass (*Lolium multiflorum*) pasture depending on stocking rate. With lower stocking rate, EW calves gained 0.17 kg/d more whereas more intense stocking rate caused EW calves to gain 0.24 kg/d less compared with TW calves. When comparing two different weaning ages (EW, 103 d; TW, 203 d) Fluharty et al. (2000) reported EW steers gained 0.46 kg/d more than TW during the time period leading up to traditional weaning. Lusby et al. (1981) found no difference in the weaning weights of EW or TW calves when EW calves remained in a dry lot. In contrast, weaning weight was lower when EW calves were allowed to graze pasture and offered creep feed on an ad libitum basis (Lusby et al., 1981). Meteer et al. (2013) reported EW calves fed a starch or fiber based diet had greater ADG than TW calves creep fed either a high starch or fiber diet, with both groups having a faster rate of gain than calves not offered creep feed. In similar studies (Myers et al., 1999a; Story et al., 2000), EW calves had increased average daily gain compared to steers weaned at a later date. Taken together, published work suggests that EW calves offered a nutrient-dense concentrate diet generally gain faster compared with calves nursing dams and grazing moderate and possibly declining quality forage. The current study results may differ in part because TW and EW calves were offered the same nutrient-dense diet ad libitum.

Feed efficiency was measured using the ratio of calf BW gain to feed or energy intake of calves alone, or feed and energy intake of the cow and calf combined. Using calf feed only, G:F of TW calves is inflated because the contribution of milk energy is not included in the ratio. The ratio of BW gain per kg of feed for EW calves was 0.207, which is comparable to data reported by Myers et al. (1999b). Feed efficiency of the pair was increased

Table 6. Effects of weaning age on 96-d drylot calf energy intake, performance, and feed efficiency

	Treatment[1]			
Item	TW	EW	SEM	*P*-Value
Initial calf age, d[2]	131	129	000	000
Cow energy intake, cumulative Mcal ME[3]	1,993	1,314	14.9	< 0.01
Calf energy intake, cumulative Mcal ME[3]				
TMR	1,031	1,231	31	< 0.01
Milk	649	000	000	000
Total	1,680	1,231	36	< 0.01
Pair cumulative Mcal feed ME[3]	3,063	2,521		
Calf body weight, kg				
January	114.5	107.4	1.8	0.02
April	238.2	202.6	5.2	< 0.01
Calf daily gain, kg	1.32	1.01	0.02	< 0.01
Calf body weight gain, kg	123	95	4.2	< 0.01
Calf gain:feed				
Calf gain:calf feed[4]	326	207	6.6	< 0.01
Pair gain:pair feed[5]	109	99	2.4	< 0.01
Calf gain:energy intake				
Calf gain:energy intake[6]	73.2	77.2	2.5	0.11
Pair gain:pair energy intake[7]	40.2	37.0	0.85	< 0.01

[1] TW = traditional weaning (226 d), EW = early weaning (130 d); *n* = 6 pens per treatment. Cows from each treatment were fed to achieve similar weight gain and calves were provided creep feed ad libitum.

[2] Age of calves at the time of early weaning.

[3] Mcal = megacalorie; ME = metabolizable energy.

[4] Calf BW gain in grams · kg of calf TMR intake^{-1}.

[5] Calf BW gain in grams · kg of TMR intake of the pair^{-1}.

[6] Calf BW gain in grams · Mcal of calf TMR intake and milk intake^{-1}.

[7] Calf BW gain in grams · Mcal of pair TMR intake^{-1}.

for the TW system ($P < 0.01$). Peterson et al. (1987) found EW cow-calf pairs to be 43.9% more efficient converting total cow and calf feed consumed into calf BW gain when cows were offered *ad libitum* access to long stem hay, and EW calves offered a nutrient-dense diet. In part, these contrasting results could be due to TW calves having access to the same nutrient-dense diet as the cows and cow's feed intake being restricted. Warner et al. (2015) weaned calves at 91 or 203 d of age. All cows and calves were fed a common diet from early to conventional weaning time within each year and location. Cows with weaned calves were limit fed and EW calves were offered ad libitum access to feed. Nursing pairs were fed the same total daily DM fed to the EW cows and calves combined. Similar to the results of the current experiment, Warner et al. (2015) found no differences in feed efficiency regardless of weaning age.

There was no difference ($P = 0.11$) in conversion of total energy intake (feed + milk) to BW gain among the two treatments. However, on a cow–calf pair basis per unit of energy intake, the TW system was more efficient ($P < 0.01$). Jenkins et al. (1991) used a similar approach where Hereford × Angus cows were limit-fed and calves had ad libitum access to creep feed. These workers calculated a feed efficiency of 36.8 g calf BW/Mcal ME intake by the cow–calf pair and this value is similar to the efficiency recorded in the current experiment (Table 6). Together, these results suggest that improved feed efficiency in the TW system can be primarily attributed to increased calf performance combined with minimal increase in lactating cow MER.

Grazing Period Performance

Traditional weaned calves entered the grazing period 22 kg heavier ($P < 0.01$, Table 7). During the grazing period, EW calves had greater average daily gain ($P < 0.01$). Overall grazing average daily gain was 16% greater for EW calves ($P < 0.01$). Compensatory gain from nutrient restriction has been a known phenomenon researched extensively, with the term compensatory gain first used extensively by Bohman (1955). Slower initial rate of gain of EW calves, followed by more rapid early grazing period gain, suggests that growth was restricted during the EW phase due to lack of milk consumption. Lewis et al. (1990) found that calves from low

Table 7. Effects of weaning age on calf body weight gain during the grazing period

	Treatment[1]			
Item	TW	EW	SEM	*P*-Value
Calf body weight, kg				
April (day 96)	237	216	5.3	< 0.01
August (day 218)	301	290	3.7	0.06
Calf daily gain, kg				
day 96 – d 218	0.52	0.60	0.04	0.03
Total calf gain, kg	64	74	3.5	< 0.01

[1] TW = traditional weaning (226 d), EW = early weaning (130 d); During the 96-d drylot period, cows from each treatment were fed to achieve similar weight gain and calves were provided creep feed ad libitum. The grazing period was initiated on day 96 and terminated on day 218 (mean for both years). Each year, calves grazed warm season perennial pasture with 0.454 kg/d of protein supplement.

Table 8. Effects of weaning age on steer finishing period performance

	Treatment[1]			
Item	TW	EW	SEM	*P*-Value
Steer body weight, kg				
August (day 219)	313	293	11.0	< 0.01
November (day 303)	498	476	16.3	< 0.01
January (day 389)	596	579	8.9	0.02
Feed intake, kg/d (dry matter basis)				
Day 219–303	7.56	9.38	0.90	0.05
Day 303–389	9.07	10.05	0.59	0.21
Day 219–389	8.30	9.70	0.74	0.09
Steer daily gain, kg				
Day 219–303	2.18	2.16	0.04	0.70
Day 303–389	1.18	1.24	0.20	0.40
Day 219–389	1.68	1.70	0.09	0.55
Steer gain:feed[2]				
Day 219–303	0.301	0.236	0.03	0.07
Day 303–389	0.131	0.124	0.02	0.30
Day 219–389	0.205	0.176	0.03	0.06
Total steer gain, kg	283	286	3.9	0.54

[1] TW = traditional weaning (226 d), EW = early weaning (130 d). During the 96-d drylot period, cows from each treatment were fed to achieve similar weight gain and calves were provided creep feed ad libitum.

[2] Kg calf BW gain kg of feed intake^{-1}.

milk producing cows exhibited compensatory gain post-weaning. Although calves from Lewis et al. (1990) all consumed milk, their results show similar compensatory gain when calves are restricted in milk consumption. However, increased grazing average daily gain by EW calves was not enough to compensate for the difference in initial BW, resulting in a tendency for lighter BW ($P = 0.06$) at the end of the grazing period.

Feedlot Performance and Carcass Characteristics

Traditional weaned steers were heavier at feedlot entry (day 218; $P < 0.01$; Table 8), reimplantation day 303; $P < 0.01$), and at harvest (day 389; $P < 0.02$). There was no difference in average daily gain at any point between treatments in the feedlot ($P \geq 0.40$). Interestingly, there was decreased DMI ($P < 0.05$) and a trend for increased feed efficiency ($P < 0.07$) of the TW steers from initiation to reimplantation. The same was true from initiation to harvest for DMI ($P < 0.09$) and G:F ($P < 0.06$). Previous literature has mixed results on the effects of weaning age and weight on feedlot performance. Others have documented improved finishing-phase feed efficiency of TW steers (Shike et al., 2007; Meteer et al. 2013). However, both Shike et al. (2007) and Meteer et al. (2013) found increased DMI and daily gain in TW calves. The reason for reduced feed intake of TW calves in this experiment is unclear. Other studies found no differences in BW gain, G:F or DMI of EW and TW calves (Arthington et al., 2005; Caldwell et al., 2011). Fluharty et al. (2000) found an increase in daily gain and DMI of TW

Table 9. Effects of weaning age on steer carcass characteristics

	Treatment[1]			
Item	TW	EW	SEM	*P*-Value
Hot carcass weight, kg	370	364	18.3	0.19
Dressing percentage	61.74	61.77	0.82	0.97
Back fat, cm	1.40	1.52	0.30	0.44
LM area, cm[2]	84.4	83.2	3.87	0.81
Yield Grade[3]	3.16	3.29	0.40	0.74
Marbling score[4]	494	485	28.7	0.58
≥Low Choice, %	90.9	95.7	—	0.53
≥Ave Choice, %	40.9	52.2	—	0.45

[1] TW = traditional weaning (226 d), EW = early weaning (130 d). During the 96-d drylot period, cows from each treatment were fed to achieve similar weight gain and calves were provided creep feed ad libitum.

[2] Longissimus muscle area.

[3] Calculated yield grade.

[4] Marbling score scale: 400 to 499 = small, 500 to 599 = modest.

steers early in the finishing phase. These workers concluded the difference was most likely due to compensatory gain of TW calves caused by modest pre-weaning nutrient restriction compared with EW calves. Myers et al. (1999a) found opposite results of increased G:F, daily gain, and lower DMI of EW calves. Nevertheless, further research is needed to determine whether finishing performance could be negatively influenced by removal of late-lactation period milk consumption. On the other hand, it is possible that availability of a nutrient-dense diet during late lactation by TW calves could positively influence finishing-phase performance.

Timing of weaning had no impact on HCW, back fat thickness, longissimus muscle area, yield grade, or marbling score ($P > 0.10$, Table 9). The influence of timing of weaning on carcass characteristics may be largely dependent on post-weaning management. For example, increased intra-muscular fat deposition and marbling score have most commonly been documented when EW calves are fed a high-concentrate diet beginning immediately after weaning and continuing through harvest (Myers et al., 1999a,b; Story et al., 2000; Shike et al., 2007; Meteer et al., 2013). In contrast, EW combined with an extended post-weaning grazing or growing period diminishes or eliminates differences in intra-muscular fat deposition (Fluharty et al., 2000; Arthington et al., 2005; Caldwell et al., 2011). Therefore, carcass composition results from the current experiment are consistent with previous literature.

Implications

Under these conditions, the original hypothesis is not supported. In fact, the current study supports that the TW system was more biologically efficient through the weaning stage of production and that there is some indication (statistical trends) of improved finishing-phase feed efficiency when calves continued to nurse their dams through the last 96 d of the traditional lactation period. Improved efficiency in the TW system could be attributed primarily to minimal increase in maintenance energy requirement of lactating cows compared with non-lactating cows, and substantially improved calf growth rate. Additional work is necessary to determine factors that contribute to the magnitude of differences in lactating and non-lactating cow maintenance requirements as well as calf preweaning performance.

Conflict of interest statement. None declared.

LITERATURE CITED

AOAC. 2012. Official methods of analysis of AOAC International. 19th ed. AOAC International, Gaithersburg, MD, USA.

Arthington, J. D., and R. S. Kalmbacher. 2003. Effect of early weaning on the performance of three-year-old, first-calf beef heifers and calves reared in the subtropics. J. Anim. Sci. 81:1136–1141. doi:10.2527/2003.8151136x

Arthington, J. D., J. W. Spears, and D. C. Miller. 2005. The effect of early weaning on feedlot performance and measures of stress in beef calves. J. Anim. Sci. 83:933–939. doi:10.2527/2005.834933x

Banta, J. P., D. L. Lalman, and R. P. Wetteman. 2005. Symposium paper: post-calving nutrition and management programs for two-year-old beef cows. Prof. Anim. Sci. 21:151–158. doi: 10.15232/S1080-7446(15)31196-7

Bellows, R. A., and R. E. Short. 1978. Effects of precalving feed level on birth weight, calving difficulty, and subsequent fertility. J. Anim. Sci. 46:1522–1528. doi: 10.2527/jas1978.4661522x

Bohman, V. R. 1955. Compensatory growth of beef cattle: the effect of hay maturity. J. Anim. Sci. 14:249–255. doi: 10.2527/jas1955.141249x

Caldwell, J. D., K. P. Coffey, W. K. Coblentz, J. A. Jennings, D. S. Hubbell III, D. L. Kreider, M. L. Looper, D. L. Galloway, E. B. Kegley, and C. F. Rosenkrans Jr. 2011. Weaning and post-weaning performance by fall-born beef calves weaned on different dates in the spring from *Neotyphodium* coenphialum-infected tall fescue pastures. Livestock Sci. 135:44–52. doi:10.1016/j.livsci.2010.06.004

Early, N. M., J. E. Sawyer, L. A. Trubenbach, C. J. Boardman, J. R. Baber, N. L. Bell, T. A. Wickersham. 2016. Effect of dietary energy intake on nutrient utilization, performance, and maintenance requirements in late gestation cows and their calves. J. Anim. Sci. 94(Suppl. 1):19 (Abstr.) doi:10.2527/ssasas2015-038

Ferrell, C. L., and T. G. Jenkins. 1985. Cow type and the nutritional environment: nutritional aspects. J. Anim. Sci. 61:725–741. doi: 10.2527/jas1985.613725x

Fluharty, F. L., S. C. Loerch, T. B. Turner, S. J. Moeller, and G. D. Lowe. 2000. Effects of weaning age and diet on growth and carcass characteristics in steers. J. Anim. Sci. 78:1759–1767. doi:10.2527/2000.7871759x

Freetly, H. C., J. A. Nienaber, and T. Brown-Brandl. 2006a. Changes in heat production by mature cows after changes in feeding level. J. Anim. Sci. 84:1429–1438. doi: 10.2527/2006.8461429x

Freetly, H. C., J. A. Nienaber, and T. Brown-Brandl. 2006b. Partitioning of energy during lactation of primiparous beef cows. J. Anim. Sci. 84:2157–2162. doi:10.2527/jas.2005-534.

Freetly, H. C., J. A. Nienaber, and T. Brown-Brandl. 2008. Partitioning of energy in pregnant beef cows during nutritionally induced body weight fluctuation. J. Anim. Sci. 86:370–377. doi:10.2527/jas.2007-0250.

Galyean, M. L., N. A. Cole, L. O. Tedeschi, and M. E. Branine. 2016. Board-invited review: efficiency of converting digestible energy to metabolizable energy and reevaluation of the california net energy system maintenance requirements and equations for predicting dietary net energy values for beef cattle. J. Anim. Sci. 94:1329–1341. doi:10.2527/jas.2015-0223.

Garrett, W. N. 1980. Energy utilization by growing cattle as determined by 72 comparative slaughter experiments. In: L. E. Mount, editor, Proc. 8th Symp. Energy Metab., Cambridge, UK. EAAP Publ. No. 26. Butterworths, London. p. 3–7.

Houghton, P. L., R. P. Lemenager, K. S. Hendrix, G. E. Moss, and T. S. Stewart. 1990. Effects of body composition, pre- and postpartum energy intake and stage of production of energy utilization by beef cows. J. Anim. Sci. 68:1447–1456. doi: 10.2527/1990.6851447x

Hudson, M. D., J. P. Banta, D. S. Buchanan, and D. L. Lalman. 2010. Effect of weaning date (normal vs. late) on performance of young and mature beef cows and their progeny in a fall calving system in the southern great plains. J. Anim. Sci. 88:1577–1587. doi:10.2527/jas.2009-1871.

Jenkins, T. G., L. V. Cundiff, and C. L. Ferrell. 1991. Differences among breed crosses of cattle in the conversion of food energy to calf weight during the preweaning interval. J. Anim. Sci. 69:2762–2769. doi: 10.2527/1991.6972762x

Jenkins, T. G., and C. L. Ferrell. 1992. Lactation characteristics of nine breeds of cattle fed various quantities of dietary energy. J. Anim. Sci. 70:1652–1660. doi: 10.2527/1992.7061652x

Lalman, D. L., D. H. Keisler, J. E. Williams, E. J. Scholljegerdes, and D. M. Mallett. 1997. Influence of postpartum weight and body condition change on duration of anestrus by undernourished suckled beef heifers. J. Anim. Sci. 75:2003–2008. doi: 10.2527/1997.7582003x

Lalman, D. L., J. E. Williams, B. W. Hess, M. G. Thomas, and D. H. Keisler. 2000. Effect of dietary energy on milk production and metabolic hormones in thin, primiparous beef heifers. J. Anim. Sci. 78:530–538. doi: 10.2527/2000.783530x

Lewis, J. M., T. J. Klopfenstein, R. A. Stock, and M. K. Nielsen. 1990. Evaluation of intensive vs extensive systems of beef production and the effect of level of beef cow milk production on postweaning performance. J. Anim. Sci. 68:2517–2524. doi:10.2527/1990.6882517x

Lusby, K. S., R. P. Wettermann, and E. J. Turman. 1981. Effects of early weaning calves from first-calf heifers on calf and heifer performance. J. Anim. Sci. 53: 1193–1197. doi: 10.2527/jas1981.5351193x

Marston, T. T., D. D. Simms, R. R. Schalles, K. O. Zoellner, L. C. Martin, and G. M. Fink. 1992. Relationship of milk production, milk expected progeny difference, and calf weaning weight in angus and simmental cow-calf pairs. J. Anim. Sci. 70:3304–3310. doi: 10.2527/1992.70113304x

Meteer, W. T., K. M. Retallick, D. B. Faulkner, J. W. Adcock, and D. W. Shike. 2013. Effects of weaning age and source of energy on beef calf performance, carcass characteristics, and economics. Prof. Anim. Sci. 29:469–481. doi: 10.15232/S1080-7446(15)30268-0

Moe, P. W., J. T. Reid, and H. F. Tyrrell. 1965. Effect of level of intake on digestibility of dietary energy by high-producing cows. J. Dairy Sci. 48:1053–1061.

Moe, P. W., H. F. Tyrrell, and W. P. Flatt. 1970. Partial efficiency of energy use for maintenance, lactation, body gain and gestation in the dairy cow. Proc. 5th Symposium on Energy Metabolism. European Ass. Anim. Prod. Publ. 13: 65–68.

Mondragon, I., J. W. Wilton. O. B. Allen, and H. Song. 1983. Stage of lactation effects, repeatabilities and influences on weaning weights of yield and composition of milk in beef cattle. Can. J. Anim. Sci. 63:751–761. doi: 10.4141

Montaño-Bermudes, M., and M. K. Nielson, and G. H. Deutscher. 1990. Energy requirements for maintenance of crossbred beef cattle with different genetic potential for milk. J. Anim. Sci. 68:2279–2288. doi: 10.2527/1990.6882279x

Myers, S. E., D. B. Faulkner, F. A. Ireland, L. L. Berger, and D. F. Parrett. 1999a. Production systems comparing early weaning to normal weaning with or without creep feeding for beef steers. J. Anim. Sci. 77:330–310. doi: 10.2527/1999.772300x

Myers, S. E., D. B. Faulkner, F. A. Ireland, and D. F. Parrett. 1999. Comparison of three weaning ages on cow-calf performance and steer carcass traits. J. Anim. Sci. 77:323–329. doi: 10.2527/1999.772323x

National Academies of Sciences, Engineering, and Medicine. 2016. Nutrient Requirements of Beef Cattle: Eighth Revised Edition. The National Academies Press, Washington, DC.

Neville, W. E., Jr. 1974. Comparison of energy requirements of non-lactating and lactating hereford cows and estimates of energetic efficiency of milk production. J. Anim. Sci. 38:681–686. doi: 10.2527/jas1974.383681x

Neville, W. E., Jr, and M. E. McCullough. 1969. Calculated energy requirements of lactating and non-lactating hereford cows. J. Anim. Sci. 29:823–829. doi: 10.2527/jas1969.295823x

NRC. 2001. Nutrient requirements of dairy cattle. 7th ed. National Academy Press, Washington, DC.

Patle, B. R., and V. D. Mudgal. 1975. Maintenance requirements for energy in cross-bred cattle. Br. J. Nutr. 33:127–139. doi: 10.1079/BJN19750018

Patle, B. R., and V. D. Mudgal. 1977. Utilization of dietary energy for maintenance, milk production and lipogenesis by lactating crossbred cows during their mid-stage of lactation. Br. J. Nutr. 37:23–33. doi: 10.1079/BJN19770004

Peterson, G. A., T. B. Turner, K. M. Irvin, M. E. Davis, H. W. Newland, and W. R. Harvey. 1987. Cow and calf performance and economic considerations of early weaning of fall-born beef calves. J. Anim. Sci. 64:15–22. doi: 10.2527/jas1987.64115x

Reynolds, C. K., and H. F. Tyrrell. 2000. Energy metabolism in lactating beef heifers. J. Anim. Sci. 78:2696–2705. doi: 10.2527/2000.78102696x

Shike, D. W., D. B. Faulkner, M. J. Cecava, D. G. Parrett, and F. A. Ireland. 2007. Effects of weaning age, creep feeding, and type of creep on steer performance, carcass traits, and economics. Prof. Anim. Sci. 23:325–332. doi: 10.15232/S1080-7446(15)30985-2

Stein, D., B. Freking, and B. Whitworth. 2015. Synchronizing heats in beef cows and heifers. In: D. L. Lalman and D. Doye, editors. Beef Cattle Manual. 7th ed. Oklahoma State University Cooperative Extension, Stillwater, OK. Pp. 289–296.

Story, C. E., R. J. Rasby, R. T. Clark, and C. T. Milton. 2000. Age of calf at weaning of spring-calving beef cows and the effect on cow and calf performance and production economics. J. Anim. Sci. 78:1403–1413. doi: 10.2527/2000.7861403x

Triplett, B. L., D. A. Neuendorff, and R. D. Randel. 1995. Influence of undegraded intake protein supplementation on milk production, weight gain, and reproductive performance in postpartum brahman cows. J. Anim. Sci. 73:3223–3229. doi: 10.2527/1995.73113223x

Trubenbach, L. A., T. A. Wickersham, V. P. Briani, and J. E. Sawyer. 2016. Dietary energy utilization in limit-fed beef cattle. J. Anim. Sci. 95(Suppl. 1):39 doi:10.2527/ssasas2017.079

Tyrrell, H. F., and P. W. Moe. 1975. Effect of intake on digestive efficiency. J. Dairy Sci. 58:1151–1163. doi: 10.3168/jds.S0022-0302(75)84694-7

Van Soest, P. J. 1963. Use of detergents in the analysis of fibrous feed. II. A rapid method for the determination of fiber and lignin. J. A.O.A.C. 46:830.

Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74:3583–3597. doi:10.3168/jds.S0022-0302(91)78551-2.

Warner, J. M., K. H. Jenkins, R. J. Rasby, M. K. Luebbe, G. E. Erickson, and T. J. Klopfenstein. 2015. The effect of calf age at weaning on cow and calf performance and feed utilization by cow-calf pairs. Prof. Anim. Sci. 31:455–461. doi: 10.15232/pas.2015-01393

Weiss, W. P., H. R. Conrad, and N. R. St. Pierre. 1992. A theoretically-based model for predicting total digestible nutrient values of forages and concentrates. Anim. Feed Sci. Technol. 39:95–110. doi: 10.1016/0377-8401(92)90034-4

Wiltbank, J. N., W. W. Rowden, J. E. Ingalls, and D. R. Zimmerman. 1964. Influence of post-partum energy level on reproductive performance of Hereford cows restricted in energy intake prior to calving. J. Anim Sci. 23:1049–1053. doi: 10.2527/jas1964.2341049x