IDENTIFICATION OF MAINTENCE ENERGY REQUIREMENTS AND ESTRUS IN BEEF COWS

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IDENTIFICATION OF MAINTENCE ENERGY REQUIREMENTS AND ESTRUS IN BEEF COWS

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CHAPTER I

INTRODUCTION

Beef producers must constantly improve the efficiency of their operation by either decreasing variable costs or increasing the quantity or quality of output. Slight improvements in feed efficiency can drastically improve profitability as feed is the highest variable cost in cattle production. About 70% of the total energy required by cows is attributed to maintenance energy requirements (Ferrell and Jenkins, 1984). Selection for more efficient cows seems possible due to genetic variation and moderate heritability for maintenance energy requirements (MR). Current methods to estimate MR are expensive, time consuming and animals are usually managed in conditions that differ from production situations. Despite considerable research a viable biomarker for selection of efficiency has not been developed for commercial application. Identification of accurate biomarkers for MR is vital to select for efficiency within breeds or herds of cows. Established tools combined with new technology may help identify biomarkers for selection purposes. Metabolic hormones and rumen temperature boluses are possible selection tools for MR in beef cows and deserve further investigation. Identification of cows that require less energy for maintenance while maintaining performance will improve efficiency of beef cattle production.

A second opportunity to improve production efficiency in beef cow operations is the use of AI. Inseminating cows to genetically superior bulls has the potential to enhance genetic traits and increase revenue. Artificial insemination can also shorten the calving season and therefore decrease labor costs if estrous synchronization is implemented. Estrous synchronization enhances the use of AI, increases the genetic potential to produce meat and milk, and can increase efficiency of beef and dairy production (Lauderdale, 2009). Improved efficiency increases profitability and decreases negative production effects on the environment. A study conducted by the Animal and Plant Health Inspection Service (USDA, 2009) representing 80% of U.S. beef cow operations and 88% of U.S. beef cows indicated that 7.9% of beef cow-calf operations use estrus synchronization while 7.6% use AI. Estrous synchronization and AI are used in about 20% of U.S. cow herds ≥ 200 cows. Time and/or labor were the primary reasons cited by producers that do not use estrous synchronization or AI with others citing cost of technology, lack of facilities, and technology too complicated or unreliable (USDA, 2009).

Unless using fixed time AI protocols, estrous detection is a prerequisite to AI. Considerable research has developed more accurate estrous detection systems that reduce time and labor. However, the ideal estrous detection system would provide continuous surveillance of cows, accurate and automatic identification of estrus, operation for the productive lifetime of the cow, and require minimal labor (Senger, 1994). Several remote sensing systems have been developed that continuously detect estrus by evaluating behavior and/or physiological changes in physical activity, mounting activity, and body temperature, without the need for handling or visual observation. However, systems currently available have limitations in either accuracy of detection, altering animal behavior, labor requirements, expense or a combination of these factors.

Recently, rumen boluses have been developed to determine and record rumen temperatures (Dye, 2007). Body temperature of cows measured by rectal temperature increased about 1.3°C on the day of estrus (Piccione et al., 2003) and rectal temperature was positively correlated (r = 0.80) with rumen temperature in beef steers (Dye, 2007). Rumen boluses allow body temperature evaluation with great frequency and minimal impact on animal behavior, and may be a useful method to detect estrus. Further investigation using rumen temperature boluses to quantify body temperature and detect estrus is warranted. Decreasing labor associated with estrous detection while maintaining a high degree of accuracy should increase the use of AI in beef cows, improving the efficiency and profitability of beef operations.

CHAPTER II

REVIEW OF LITERATURE

ENERGETIC EFFICIENCY OF BEEF CATTLE

The historical development of nutritional energetics in this review was described by Johnson et al. (2003). Dietary energy utilization has been pursued by researches dating back to the mid 15th century. Antoine Lavoisier (1743-1794) developed the concept that life is primarily a combustion process by relating metabolism to combustion. Next the Laws of Thermodynamics and the Law of Hess were developed. Berthelot (1827-1907) developed the adiabatic bomb calorimeter, enabling researchers to accurately quantify the energy content of organic compounds, feed, feces, and urine. Baron Justus Von Liebig (1803-1873) first proposed that foods be divided into carbohydrates, fats, and proteins, because they differ in metabolism. The open-circuit respiration apparatus was soon developed by Max Von Pettenkofer (1818-1901) to study gas exchange and heat production. Much of the early work in this area was done by Carl Von Voit and his students. Research in this area continued until 1965 when Brouwer developed an equation (Brouwer equation) to calculate heat production from indirect calorimetry measurements of oxygen consumption, carbon dioxide production, methane production, and urinary nitrogen. The direct measurement of heat production by the animal, known as direct calorimetry, is based on the work of Lavoisier. Modern calorimeters, used to better understand the relationship between heat production and energetics, were developed from the principles of Lavoisier and others. Metabolizable energy (ME) is defined as gross energy (E) minus fecal energy (FE), urinary energy (UE), and gaseous energy (GE) losses: ME = DE – (UE + GE). Digestible energy (DE) is gross energy minus energy lost in feces. Metabolizable energy can appear only as heat production (HE) or retained energy (RE), therefore: ME = HE + RE (NRC, 1996). Armsby (1903, 1917) used respiration calorimetry to define ME as the net energy plus heat increment of feeding; setting the stage for the basis of the net energy systems used today. Heat production is equal to the animal's net energy required for maintenance (NE_m) at zero feed intake (NRC, 1996).

The term efficiency requires a numerator and a denominator with units to describe each (Johnson et al., 2003). The numerator is the caloric content while the denominator is the units of diet (weight, Mcal, TDN, ME, NE, etc.). Many ratios with different units have been used to describe energetic efficiency of beef cattle (Johnson et al., 2003).

The maintenance energy requirement (MR) is defined as the amount of feed energy intake resulting in no net loss or gain of energy from animal body tissues (NRC, 1996). Although maintenance may be a theoretical condition in production situations, it is helpful to separate MR from energy requirements for production such as growth or lactation (NRC, 1996). The greatest variable cost in beef production is MR of the cow herd; about 70% of the total energy required by cows is attributed to MR (Ferrell and Jenkins, 1984).

Measuring efficiency in cattle

The three primary methods that have been used to measure MR of cattle are feeding trials, calorimetric methods, and comparative slaughter. Long-term feeding trials allow researchers to estimate feed required to maintain BW with large numbers of cattle. Feeding trials determine the quantity of feed required for maintenance or determine the body weight maintained after feeding a predetermined amount of feed (NRC, 1996). Animals can also be fed to allow small BW gains or losses and MR are calculated with a regression model including energy intake, live weight, and live weight gain/loss (McDonald et al., 2002). Feeding trials allow animals to be managed similar to production situations.

Calorimetric methods date back to the early 1900s (Von Voit) and have developed many of the concepts that make up energy equations and feeding systems used today. This method directly estimates MR by measuring fasting heat production. Heat production is a measure of fasting metabolism which equates to net energy required for maintenance, NE_m (NRC, 1996). Heat production has been measured to study energetics and efficiency in many species with environmental controlled chambers. Nielsen et al. (1997-2009) have extensively studied heat production as it relates to maintenance requirements in lines of mice divergently selected for heat loss. Maintenance energy requirements have also been measured indirectly by respiratory exchange and oxygen consumption of the whole animal and specific tissues as an indirect estimation of heat production. Calorimetric methods are generally complex and costly limiting the number of animals that can be measured (NRC, 1996), especially large animals like cattle. Management of animals in calorimetric chambers is far removed from their natural environment (McDonald et al., 2002) limiting practical application of data obtained (NRC, 1996).

Heart rate (HR) has recently been explored as a means of quantifying energy expenditure in cattle (Brosh et al., 2006) and boer goats (Puchala et al., 2009). Heat production or energy expenditure can be quantified indirectly by measuring oxygen consumption; because oxygen is transferred to tissues through the heart energy expenditure can be estimated with a regression of HR and oxygen consumption (Brosh, 2007). This method allows quantification of energy expenditure by animals in their natural environment, such as grazing (Brosh, 2007). Although this technique is exciting it may have limited application as equipment must be calibrated to each animal and animals must not be stressed by the measurement process or during calibration (Johnson et al., 2003). As this technology advances and equipment becomes economically viable, the use of HR may provide producers a tool to evaluate energy and health status of individual animals (Brosh, 2007).

Infrared imaging thermography can be used to measure radiation emitted by animals and has been investigated as an indirect measure of heat production (Montanholi et al., 2008a). The correlation between temperatures at different body locations with heat production, ranged from 0.58 for the rear area to 0.88 for foot temperature, and foot temperature explained nearly 80% of the variation in heat production (Montanholi et al., 2008a). Foot temperature was positively correlated (right foot = 0.43, left foot = 0.38) with residual feed intake (RFI); more efficient bulls (low RFI) had lower temperatures for body extremities (cheek and foot) compared with less efficient bulls (Montanholi et al., 2008a). Infrared thermography explained 59% of the variation in RFI (Montanholi et al., 2008b). This method is a non-invasive relatively inexpensive technique to measure body temperature or heat production in large animals. Infrared thermography has the potential to measure feed efficiency and may be a useful tool for selecting more efficient animals. However, further research and more replications should be completed to verify the accuracy and application of this technology (Montanholi et al., 2009).

Lawes and Gilbert (1861) first used the comparative slaughter method in their manuscript entitled: On the composition of oxen, sheep and pigs and of their increase whilst fattening. Work by Garrett, (1959), Lofgreen (1965) and Lofgreen and Garrett (1968) further developed comparative slaughter techniques, leading to the basis of the energy systems in the current NRC (1984; 1996). This method measures initial and final body composition, energy intake, and retained energy. Maintenance requirements are calculated from the difference between energy intake and retained energy. Comparative slaughter allows animals to be managed similar to normal production situations, however, accurate measures of body composition at the beginning and end of the trial are essential (NRC, 1996). The NE_m requirement for beef cattle, derived from growing steers and heifers is 0.077 $Mcal/EBW^{0.75}$ and EBW is the average empty body weight in kilograms (Lofgreen and Garrett, 1968). The NRC (1996) adjusts this formula for beef cows according to breed, physiological state, activity, and ME intake vs. retained energy and body condition (Level 1 Model). This model also includes adjustments for environmental conditions and animal insulation (NRC, 1996).

Evans et al. (2002) indirectly estimated mature cow MR using EPD based on mature weight and milk production. This equation indicated the genetic trend for MR increased 3.8 Mcal per yr from 1966 to 1995 in mature Red Angus cattle (Evans et al., 2002). Although EPD for MR are useful genetic selection tools, research is necessary to understand the physiological mechanisms involved in MR of cows. Selection using an

EPD for MR should be monitored closely to prevent unintentional selection for negative production traits.

Factors contributing to variation in efficiency

Breed or type, sex, age, physiological state, and body composition, as well as environmental impacts, all contribute to variation in MR of cows. Maintenance requirements are closely related to a fractional power of empty body weight (EBW) rather than $EBW^{1.0}$ (Brody, 1945; Kleiber, 1961; NRC, 1996). The correct power to scale energy requirements for body weight, referred to as metabolic body weight, is a subject of debate. After reviewing literature in several species, Blaxter (1972) stated that when fasting is measured on mature animals with varying BW, the exponent used for metabolic BW should be in the range of 0.83 to 0.93 (Johnson et al., 2003). However, other reviews have demonstrated no advantage to using exponents other than 0.75 (AAC, 1990; Garrett and Johnson, 1983). Indeed, $EBW^{0.75}$ is widely adopted to scale energy requirements for body weight (NRC, 1996).

Differences in MR within and between breeds have been identified (Ferrell and Jenkins, 1984; DiCostanzo et al., 1990; Derno et al., 2005). Blaxter and Wainman (1966) used calorimetry to determine that Ayrshire steers had 20% higher fasting heat production (FHP; kcal/$BW^{0.75}$) than black Angus type steers, and 6% greater MR than crosses of the two breeds. Holstein steers had 12% greater MR compared with that of Hereford steers (Garrett, 1971). Simmental bulls had 14% greater FHP compared with Hereford bulls (Ferrell and Jenkins, 1985b). Maintenance energy requirements of males and females from different breeds and breed crosses ranged from 123 to 169 Kcal·$BW^{-0.75}$·d^{-1} (Thompson et al., 1983; Ferrell and Jenkins, 1984; Solis et al., 1988; Montano-

Bermudez et al., 1990; Laurenz et al., 1991; Reid et al., 1991). Variation in MR appears to be positively correlated with genetic potential for growth and milk production (Ferrell and Jenkins, 1985b). Ferrell and Jenkins (1984) identified ME_m values ($Kcal \cdot BW^{-0.75} \cdot d^{-1}$) of mature Angus x Hereford or Hereford x Angus (130); Charolais x Angus or Charolais x Hereford (129); Jersey x Angus or Jersey x Hereford (145); and Simmental x Angus or Simmental x Hereford (160) cows. Cows with greater MR had greater milk production potential with no effect of cow size on ME_m. Similarly, Thompson et al. (1983) found that Angus x Holstein cows had greater MR (140 $Kcal \cdot BW^{-0.75} \cdot d^{-1}$) compared with Angus x Hereford cows (128 $Kcal \cdot BW^{-0.75} \cdot d^{-1}$). Montano-Bermudez et al. (1990) found that MEm differed for cows with low, medium and high genetic potential for milk production. Nonpregnant, nonlactating Simmental cows had greater MR compared with Angus cows in similar physiological state (Laurenz et al., 1991). Direct comparison of this research is difficult due to the diversity of breeds, methodologies, and conditions. However, the subcommittee on beef cattle nutrition (NRC, 1996) concluded Bos *indicus* breeds require about 10% less energy for maintenance than Bos *taurus* beef breeds, and dairy or dual-purpose Bos *taurus* breeds require about 20% more energy for maintenance than beef breeds.

Bulls require about 15% greater energy for maintenance than steers or heifers of the same genotype (NRC, 1996). Maintenance requirement per unit size (BW) is thought to diminish as animals get older (Blaxter, 1962; Graham et al., 1974; Graham, 1980), however, there is evidence that does not support this theory (Neville, 1971; Taylor et al., 1981). After cows reach maturity it appears that MR remain relatively stable throughout their productive life. However, the physiological state of cows also alters MR. Lactating

Hereford cows required 30% greater energy for maintenance compared with nonlactating cows (Neville, 1974). Ferrell and Jenkins (1985b) found that MR differed from 10 to 20% between dry and lactating cows. Similarly, lactating cows have about 20% greater MR than nonlactating cows (NRC, 1996).

Differences in body condition or body composition can influence MR of mature beef cows (Klosterman et al., 1968; Thompson et al., 1983; DiCostanzo et al., 1990). Fat tissue insulates the body during cold conditions, reducing the MR of swine and cattle (Thompson et al., 1983; Tess et al., 1984; Wagner et al., 1988). Klosterman et al. (1968) reported a negative correlation between BCS and energy requirements of Hereford and Charolais cows. Cows in low condition lost weight while those in high condition tended to gain weight when fed similar amounts of feed per unit BW. Similarly, MR of thin Angus x Hereford cows (131.5 $\mathrm{Kcal \cdot kg\ BW^{-0.75}}$) were 6.1% greater than cows in moderate (123.5 $\mathrm{Kcal \cdot kg\ BW^{-0.75}}$) condition (Thompson et al., 1983). Metabolic BW ($\mathrm{BW^{0.75}}$) does not completely explain energy requirements of cows with different BCS because less energy is required to maintain fat than lean tissue (Crooker et al., 1991).

The MR of sheep is more closely related to body lean mass than body fat mass (Graham, 1967; Graham et al., 1974; Ferrell et al., 1979). Similarly, lean tissue has a greater impact on MR than fat stores in swine (Tess et al., 1984) and cattle (Webster, 1977; DiCostanzo et al., 1990; Baker et al., 1991). Cows equal in BW that differ in BCS have different amounts of lean body mass, which should cause them to differ in MR (Crooker et al., 1991). DiCostanzo et al. (1990) found mature, nonpregnant, nonlactating Angus cows need 9.3 times greater energy to maintain protein than to maintain fat stores. Although skeletal muscle is the largest source of protein in the body, Ferrell and Jenkins

(1985b) indicated that emphasis on economically important tissues in research has allowed biologically important tissues to be overlooked. The rate of synthesis and degradation of visceral organs protein is greater than that of skeletal muscle (Lobley et al., 1980). The relationship between fasting heat production (FHP) and visceral protein is greater than that of FHP with weight of carcass protein in pigs (Tess et al., 1984; Noblet et al., 1999). Oxygen consumption (and therefore heat production) increased as visceral organ mass increased in lambs (Burrin et al., 1990) and cattle (Reynolds et al., 1991). The liver and gastrointestinal tract are responsible for a great amount of energy expended by the whole body (Ferrell and Jenkins, 1985a; McBride and Kelly, 1990). The liver and gastrointestinal tract comprises 8 to 14% of total body protein and synthesizes 25 to 45% of total body protein; skeletal muscle accounts for 50% of total body protein yet only synthesizes 15 to 20% of total body protein (Lobley, 2002). Noblet et al. (1999) reported visceral organ mass contributed three times more to MR of pigs than lean mass.

Cattle produce heat from tissue metabolism and fermentation, and dissipate heat by evaporation, radiation, convection, and conduction. Body temperature homeostasis is maintained by regulating heat production and dissipation. Heat production is independent of ambient temperature within the thermoneutral zone and is primarily determined by feed intake and efficiency of use. Briefly, as ambient temperatures reach the limits of the zone of thermoneutrality (upper critical temperature or lower critical temperature) the animal must produce more heat to stay warm or dissipate heat to cool the body, and therefore MR increase (NRC, 1996). The impact of environmental changes on MR of animals, due to location or season, is usually associated with changes in ambient temperature and/or feed availability (Ferrell and Jenkins, 1985a; Laurenz et al., 1991; Calegare et al., 2007). Animals respond to climatic conditions by altering behavior (grouping, change activity, seek shade or wind break, wading in water, etc.) and physiological adaptations (alter basal metabolism, respiration rate, feed and water consumption, feed rate of passage, hair coat, and body composition). Considerable variation exists in behavioral and physiological adaptation to environment changes within and between breeds and genotypes of cattle (NRC, 1996). Season, independent of temperature, may also impact MR of cattle. Lower MR were noted in sheep (Christopherson et al., 1979), cattle (Blaxter and Boyne, 1982) and bison (Webster et al., 1982) during the fall of the year (NRC, 1996). Mature cows appear to require less energy to maintain weight during the fall compared to winter or spring (Byers et al., 1985), however, Laurenz et al. (1991) indicated there are breed differences in response to season.

Feed intake (FI) directly impacts total heat production and energy required for maintenance. Heat production is dynamic and positively associated with FI in beef cows (Freetly and Nienaber, 1998; Freetly et al., 2008). Metabolic rates of cows fluctuate with changes in nutrient or forage availability. Estimation of MR may be influenced by changes in feed allowance or intake and may be confounded with environmental impacts such as season and temperature. Previous plane of nutrition and compensatory gain also influence MR (NRC, 1996). These interactions must be considered when designing experiments to estimate MR as well as in production settings.

Activity requires energy and contributes to variation in MR, however, until recently this relationship has been difficult to quantify. Mice divergently selected for high heat loss (low efficiency) had greater locomotion activity compared with low heat loss lines (Mousel et al., 2001). Grazing animals expend more energy than penned cattle; however the extent of grazing on MR is not well documented. Energy expenditure from activity is impacted by factors such as forage quality/availability, topography, distribution of water, genotype, etc. The energy cost of grazing activity and locomotion during grazing were 6.14 and 6.07 J/(kg $BW^{-0.75}\cdot m$), respectively, for beef cows measured with heart-rate monitors, Global Positioning System (GPS) collars, and motion sensors (Brosh et al., 2006).

Maintenance energy requirements increase in response to disease or infection. Immune responses to such events requires energy and therefore increases MR (NRC, 1996). Nervous or poor tempered cattle may expend more energy and therefore have greater MR compared with more docile cattle (Crooker et al., 1991).

Many so called “maintenance control factors” have been suggested such as: thyroid hormone, Na+/K+ ATPase, proton leak, uncoupling proteins, leptin, acetyl-CoA carboxylase 2, malonyl CoA, sympathetic tone, α_2-agonists, and calcium/calmodulin-dependent muscle protein kinase (Johnson et al., 2003). The relationship between uncoupling proteins and/or mitochondrial function in multiple tissues has been studied in mice (McDaneld et al., 2002) and cattle (Kolath et al., 2006a; 2006b). Further study of the mechanisms mediating mitochondrial function may help identify biomarkers to predict residual feed intake and/or feed efficiency in livestock and poultry (Bottje and Carstens, 2009). A better understanding of physiological factors suggested to control animal MR has not resulted in selection of more efficient animals, yet research has improved energy requirements of groups of animals and expanded our knowledge of this complex issue (Johnson et al., 2003).

Individual animal variation and heritability

The CV of MR in groups of beef cattle ranges from 5 to 35% (DiCostanzo et al., 1990; Johnson et al., 2003; Prado, 2009) suggesting an opportunity for improved efficiency through selection because of variation within breeds. Considerable differences in ME_m among animals exists, with the greatest difference being 26.6% in Angus cows (DiCostanzo et al., 1990) and 22.8% in Hereford steers (Derno et al., 2005). Carstens et al. (1987; 1989) estimated heritability of ME_m to be 0.71 and 0.49 at 9 and 20 mo of age in identical twin beef cattle. Hotovy et al. (1991) also observed ME_m to be moderately heritable (0.52) in monozygous twins. Mice divergently selected for heat loss had heritabilities of 0.31 and 0.26 for high and low heat loss lines, respectively (Nielsen et al., 1997). These studies indicate that improvement in beef cow efficiency through selection is possible due to substantial inter animal variation and moderate heritability for MR.

Residual feed intake

Residual feed intake (RFI) is a measure of feed efficiency that is strongly related to DMI, but independent of level of production (growth) and mature size (Herd and Arthur, 2009). Koch et al. (1963) first described the concept of RFI in beef cattle. Expected feed intake for a given level of production is compared to actual feed intake to get a residual portion. This residual is used to identify animals that deviate from expected feed intake and to classify cattle as high efficiency (negative RFI) or low efficiency (positive RFI) animals. Although estimation of RFI is usually done in young growing cattle, the correlation between RFI in growing cattle and mature cows is significant (Herd et al., 2003). Herd and Arthur (2009) indicated the five major physiological processes that likely contribute to variation in RFI are feed intake, digestion of feed, metabolism, activity, and thermoregulation. Residual feed intake is positively correlated with heat production (Basarb et al., 2003; Nkrumah et al., 2006). Greater efficiency in low RFI steers compared with high RFI steers may be a result of decreased methane production (Nkrumah et al., 2006; Hegarty et al., 2007) and increased digestibility (Nkrumah et al., 2006). Differences in metabolic efficiency may explain why low RFI steers produce less heat compared with high RFI steers (Nkrumah et al., 2006). Low RFI steers had decreased DMI and decreased visceral organ mass compared with high RFI steers (Basarb et al., 2003). Less efficient pigs (Tess et al., 1984; Noblet et al., 1999), sheep (Burrin et al., 1990), and cattle (Ferrell and Jenkins, 1984; Wagner et al., 1988; Reynolds et al., 1991) have greater visceral organ mass. Although RFI may not be a tool for direct estimation of mature cow feed efficiency, selection for low RFI in bulls may indirectly improve efficiency in subsequent generations of mature cows. However, Bormann et al. (2008) found heifers sired by low or high RFI bulls had similar RFI, feed conversion ratio and rate of gain. The relationships between RFI selection in bulls and subsequent efficiency in growing heifers and mature cows is not established. Selection for improved RFI may result in heifers that attain puberty at older ages, however, it appears female reproduction is not otherwise negatively impacted (Lancaster, 2008b). Future research should focus on the relationship between RFI and long-term reproductive function of cows (Lancaster, 2008b).

The genetic regulation of RFI is currently in early research stages with limited results. Despite the identification of multiple genetic markers for RFI in beef cattle, a major gene affecting RFI has not been found; however, combinations of markers have been related to the genetic variation for RFI. Future research should focus on the identification of mechanisms contributing to variation in RFI. Physiological and molecular genetics information used together will lead to the ultimate goal of developing an accurate, cost effective commercial test for selection of efficient animals (Herd and Arthur, 2009). Selection for more efficient animals with RFI could potentially reduce maintenance costs in the cow herd by 9 to 10%, reduce feed intake by 10 to 12%, reduce methane emissions by 25 to 30% (Nkrumah et al., 2006; Hegarty et al., 2007), and reduce manure production by 15 to 20% (Basarb et al., 2003). The physiological and molecular mechanisms that regulate efficiency may be similar between growing animals with low RFI and mature cows with low MR.

Selection and future direction

Knowledge about domestic livestock energetic efficiency expanded exponentially in the 20th century and has continued to do so in the last decade. However, very little improvement in beef cattle efficiency has been made, as MR of cattle today are similar to MR estimated by Kellner (1909). However, future energetic efficiency research should focus on methods to assess individual animal efficiency, particularly variations in MR of mature beef cows (Johnson et al., 2003). A practical method to identify individuals with high and low efficiency must be developed to replace costly and time consuming respiration or slaughter methods (Johnson et al., 2003).

Metabolic hormones may regulate biological processes that contribute to MR. Plasma concentrations of insulin-like growth factor-I (IGF-I), insulin, and thryroxine (T_4) of beef cows are influenced by dietary energy and protein intake (Ciccioli et al., 2003; Lents et al., 2005). Nutrient uptake also influences plasma concentrations of glucose (Bossis et al., 1999; Ciccioli et al., 2003), and non-esterfied fatty acids (Richards et al., 1989a; Bossis et al., 2000). Insulin-like growth factor is a protein hormone released by the liver and peripheral tissues in response to growth hormone. IGF-I alters glucose and amino acid metabolism, protein accretion (Jones and Clemmons, 1995) and increases protein synthesis compared with degradation (Lobley, 1992). These studies suggest that IGF-I impacts growth, carcass composition and feed efficiency and may help identify more efficient animals.

Insulin-like growth factor-I has been associated with increased feed efficiency (Bishop et al., 1989; Stick et al., 1998) and has been used as an indirect selection method for RFI selection (Davis and Simmen, 2006). The relationship between RFI and IGF-I has been difficult to understand because of conflicting results among studies (Moore et al., 2009); some studies have identified positive correlations (Moore et al., 2005), while others have found minimal or no correlation (Lancaster et al., 2008b). The relationship between IGF-I and RFI is complex and may be influenced by the composition of growth and age at time of sampling (Lancaster et al., 2008b). The reliability of IGF-I as a biomarker and the extent of the relationship between IGF-I and RFI is currently in question, and more research is necessary before further industry application (Moore et al., 2009). Lancaster (2008a) indicated a lack of knowledge regarding animal variation in concentrations of IGF-I and the relationship between IGF-I and feed efficiency. Concentrations of IGF-I have not been quantified in mature cows with low and high MR.

Thyroid hormones have a central role in energy homeostasis and body temperature regulation. Metabolism of carbohydrates, lipids, and proteins are all partially controlled by thyroid hormones (Moreno et al., 2008). Thyroid hormones act on nearly every cell in the body and stimulate heat generation as a means of thermoregulation.

Plasma concentrations of thyroxine (T_4) are associated with feed intake in cattle (Richards et al., 1995; Ciccioli et al., 2003). Low-producing (milk) dairy heifers had greater T_4 than high-producing heifers (Bitman et al., 1984). Thyroid hormones are an indicator of metabolism and may be beneficial as a biomarker for MR identification and/or selection.

Rectal temperatures were positively associated with MR of beef steers (r = 0.70) (Derno et al., 2005) and mice (Mousel et al., 2001; Kgwatalala et al., 2004). Core body temperature averaged 0.51°C greater in mice selected for high heat loss (less efficient) compared with mice selected for low heat loss (Mousel et al., 2001). Variation in heat loss is the primary contributing factor to variation in core body temperature (Refinetti and Menaker, 1992). Heat production/loss in non-growing animals is highly correlated with feed intake and MR (Nielsen et al., 1997). Heat production is greater in growing cattle with high RFI compared with low RFI (Basarb et al., 2003). Metabolizable energy that is not used as energy or stored in body tissues is lost as heat, therefore, more efficient animals will convert greater proportions of ME into tissue rather than heat production, compared with less efficient animals. Rumen boluses have been developed to determine and record rumen temperatures (Dye, 2007). Rectal temperature was positively correlated (r = 0.80) with rumen temperature in beef steers (Dye, 2007). Rumen boluses allow body temperature evaluation with great frequency and minimal impact on animal behavior and may be a useful method to identify variation in MR of cows.

Identification of accurate biomarkers that classify cows with low and high MR is essential to select for efficiency within breeds and/or types of cows. Biomarkers for selection purposes must be both accurate and economical to be successfully adopted by beef cattle producers. Body temperature and concentrations of hormones in plasma of mature beef cows with different MR have not been identified. Radioimunoassays for metabolic hormones and rumen temperature boluses are possible selection tools for MR in beef cows and deserve further investigation.

ESTRUS IN THE COW

At puberty, females begin a series of predictable reproductive events called the estrous cycle. Estrus is the period when females are sexual receptivity during the 21 d bovine estrous cycle. Estrous cycles begin at estrus (heat) and end at the subsequent estrus, providing females repeated opportunities to become sexually receptive and conceive. Females continue this cyclic pattern throughout their adult life unless interrupted by pregnancy, nursing, inadequate nutrition, or unusual environmental or other stress. The cycle can be divided into the luteal phase and the follicular phase, named for the primary structure present on the ovary during each phase. The follicular phase begins with regression of the corpora lutea (CL) and ends at ovulation. This phase is characterized by growing follicles that primarily produce estradiol. After ovulation, the luteal phase is characterized by formation of the CL, which produces progesterone. This phase represents about 80% of the estrous cycle in the bovine, while the follicular phase represents the remaining 20%. A host of interactions between the hypothalamus, pituitary, ovary and uterus control reproduction in the bovine.

Estrus is the most easily recognized stage of the cycle because of alterations in animal behavior. Cows entering estrus have increased locomotion, appear nervous, attempt to mount other animals, and seek others to mount them. Many behavioral changes indicate that a females is in estrus, but the best indication that a cow is in estrus is to see her stand when mounted by other animals (Foote, 1975). Estrous behavior is influenced by many social, environmental, and animal factors and is quite variable between animals.

Endocrine control of estrus

The transition from the luteal to the follicular phase is marked by regression of the CL resulting in reduced concentrations of progesterone in plasma. Near the end of the luteal phase, the CL produces oxytocin in response to uterine Prostaglandin $F_{2\alpha}$ ($PGF_{2\alpha}$); increased oxytocin causes the uterus to produce and release greater $PGF_{2\alpha}$ (Flint et al., 1990; Silvia et al., 1991). This $PGF_{2\alpha}$ is transported to the ovary by utero-ovarian blood vessel counter current exchange where it ultimately causes demise of the CL. Plasma concentrations of progesterone decrease to less than 1 ng/mL within 48 h of natural luteolysis (Henricks et al., 1970; Swanson et al., 1972; Wettemann et al., 1972). This is very important because progesterone inhibits estrous behavior (Ford, 1985; Davidge et al., 1987; Fabre-Nys and Martin, 1991). When progesterone concentrations reach a threshold level, estrus is inhibited even when estrus-like concentrations of estradiol are present (Davidge et al., 1987; Rajamahendran et al., 1979; Vailes and Britt, 1990; Fabre-Nys and Martin, 1991). Decreased concentrations of progesterone remove negative feedback of progesterone on the hypothalamus, allowing increased pulsatile secretion of GnRH. This stimulates pulsatile release of FSH and LH from the adenohypothesis, initiating follicular growth and maturation. Soon the dominant follicle produces greater amounts of estradiol, causing plasma concentrations of estradiol to increase (Dobson, 1978; De Silva et al., 1981; Ireland et al., 1984). The ovulatory LH surge from the adenohypophysis and the onset of estrous behavior coincide with this estradiol peak (Wettemann et al., 1972; Echternkamp and Hansel, 1973; Chenault et al., 1975; Lemon et al., 1975; Walton et al., 1987; Rajamahendran and Taylor, 1991). Estradiol, in the relative absence of progesterone, stimulates the hypothalamus to induce estrus. Ovariectomized cattle initiated estrus in response to estradiol treatement (Asdell et al., 1945; Ray, 1965; Carrick and Shelton, 1969; Lefebvre and Block, 1992; Vailes et al., 1992). Additionally, immunization of cattle against estradiol inhibited estrous behavior when animals had estrus-like serum concentrations of estradiol (Martin et al., 1978). Large doses of testosterone given to intact females induced estrus (Kiser et al., 1977; Allrich, 1994); however, results were inconsistent in ovariectomized females (Katz et al., 1980; Nessan and King, 1981). Induction of estrous behavior does not appear to be as pronounced in response to testosterone alone compared with exogenous estradiol.

Stressed animals have been found to delay, shorten, or fail to express estrus. Sources of stress include environmental, such as heat stress, handling or management, poor health/sickness, and transporting animals. Dexamethasone, a synthetic glucocorticoid, reduced the percentage of heifers in estrus (Cook et al., 1987). Heifers subjected to repeated stress had increased concentrations of corticosteroid during the follicular phase and absence of the surge of LH in some heifers but did not influence estrus (Stoebel and Moberg, 1982). It appears that most animals can withstand moderate levels of stress without drastically altering hormone profiles or estrous behavior prior to ovulation.

Estrous behavior

Estrous cows undergo many physiological and behavioral changes that are easily detected by visually observation, often referred to as primary characteristics of estrous behavior. The best indication that a cow is in estrus is to see her stand when mounted by other animals (Foote, 1975). Females enter estrus gradually by increasing locomotion, nervousness and attempts to mount other animals. Cows usually do not stand when mounted by males or other females during early stages of estrus. As estrus progresses, females become more willing to accept mating. Willingness to accept mating is known as standing estrus and the characteristic mounting posture during this time is termed lordosis. Both the duration and number of mounts received during standing estrus is variable. Duration of estrus for dairy cows under continuous visual observation (Pennington et al., 1985; Walton et al., 1987) or HeatWatch® (Walker et al., 1996; Dransfield et al., 1998; Xu et al., 1998) ranged from 7 to 13 h with 8 to 33 mounts per estrus. White et al. (2002) found the mean duration of estrus was 15 h with an average of 48 mounts received per estrus. Beef heifers were estrus for 14 h with 50 mounts received during standing estrus (Stevenson et al., 1996). The duration of estrus for Bos indicus females was between 7 and 8 h with 19 to 25 mounts per estrus (Rae et al., 1999; Yelich et al., 1999). Estrus usually lasts from 12 to 16 h but can vary from 2 to 28 h (Hurnik and King, 1987; Allrich, 1993). Lopez et al. (2004) found high milk production decreased duration of estrus in dairy cows, possibly due to decreased concentrations of estradiol. Reported duration and number of mounts during standing estrus may vary by estrous detection method. Ovulation usually occurred 31.1 ± 0.6 h after onset of estrus and was not influenced by season (White et al., 2002). Cows that jump or mount other cows can be either estrus or non-estrus (Williamson et al., 1972a; Hurnik et al., 1975). Vaca et al. (1985) found 87% of attempted and successful mounts were performed by estrous cows when observing estrus 30 min per day. Cows can ovulate with limited or no visual signs of estrous behavior, often associated with the first postpartum ovulation. Ovulations without estrous behavior during the first ovulation postpartum occurred in 50 to 94% of cows (King et al., 1976; Schams et al., 1978; Savio et al., 1990; Kyle et al., 1992) and the variation is dependent on frequency of estrous detection.

The definitive sign that cows are in estrus is receptivity to mounting, however, a host of other physiological changes occur at estrus that may aid in identification of estrous cows. Foote (1975) reported other possible signs of estrus: cow is restless, noisy or vocal and active; cow nudges, sniffs, and mounts others; cow raises tail when contacted by others; vulva is pink and swollen; and clear mucus discharge. Increased activity by estrous animals has been consistently reported. Amount of time standing and ambulation increased 32 and 40%, respectively in confined beef cows on the day of estrus compared with 4 d before and 4 d after estrus (Hurnik and King, 1987). Similarly, ambulation (mostly measured by pedometers) increased during estrus (Kiddy, 1977; Lewis and Newman, 1984; Pennington and Callahan, 1986; Maatje et al., 1997).

Social interaction such as sniffing, rubbing, licking, chin-pressing, and aggressive behavior (butting) peak during the first hour of sexual receptivity (Hurnik and King, 1987). However, these activities are not limited to this time and are not a reliable indication of onset of estrus as not all cows exhibit these behaviors. In addition, many cows did not consistently display these activities during consecutive estrous events (Hurnik and King, 1987). Clear vaginal mucus on the exterior genitalia is often associated with estrus. Mucus usually hangs from the vulva and can be seen on the tail and hindquarters of females that have been mounted by other animals. Vaginal mucus was present 50% of the time at AI after detected estrus in a study of 732 dairy cows and heifers and conception rate was greater (48 vs. 39%) when mucus was present at AI (Stevenson et al., 1983). Mucus was present in 64% of estrus events in Zebu cattle (Mattoni et al., 1988) and 68% of dairy cows (Hackett and McAllister, 1984). In addition vaginal pH decreased (Schilling and Zust, 1968; Lewis and Newman, 1984; Fisher et al., 2008) and vaginal mucus conductivity was altered (Lewis et al., 1989; Fisher et al., 2008) at estrus. Fisher et al. (2008) indicated that vaginal mucus conductivity does not appear to a viable option to identify the time of the LH surge due to considerable variation.

***Factors influencing estrous behavior* -** Many factors contribute to the degree of estrous behavior in females. Primary influences of estrous behavior include animal factors, facilities and handling, environment, time of day and/or management, and social factors. These factors can either stimulate or inhibit the degree of estrous behavior observed.

***Animal factors* -** Age or parity influences the degree of estrous behavior. Multiparous dairy cows were in estrus about 50% more time than premiparous cows (Walker et al., 1996). Cows that were 5 and 6 yr of age received nearly twice as many mounts as 2 to 4 yr old cows (Mathew et al., 1999). As days postpartum increased, the duration of estrus (Pollock and Hurnick, 1979; Hurnik and King, 1987) and percentage of dairy cows detected in estrus by twice daily visual observation (Peter and Bosu, 1986) increased. Morrow (1969) found that by about 60 d postpartum most dairy cows ovulated two to three times and 64% were observed in estrus. The mean postpartum interval to first behavioral estrus was about 52 d in beef cows (Hurnik and King, 1987), 79 d in Angus cows (Morris et al., 1978), and 35 d in Holstein cows (King et al., 1976). Duration of the post partum anestrous interval varies with breed, age, body condition, plane of nutrition, and milk production. The interval from calving to first estrus was greater for beef cows in thin (< 5) than moderate (≥ 5) BCS (Lents et al., 2008). The interval from parturition to first visual estrus by twice daily observation was longer in high producing dairy cows compared with low producers (Harrison et al., 1989). In addition, duration of estrus was greater for heat stressed dairy cows in good condition compared with thin condition cows (Wolfenson et al., 1988). Harison et al. (1990) found that dairy cows that produced more milk had weaker signs of estrus than cows that produced less milk, when visually detected 30 min after each milking.

Facilities and handling - Size of pens, number of animals per pen, and footing surface can influence estrous behavior. Dairy cows and heifers had more mounts in a barn than when housed in drylot or pasture (Gwazdauskas et al., 1983). Additionally, Zebu cows fed in a small drylot at night and allowed to graze pasture during daylight hours had greater estrous activity (mounts) in drylot than on pasture, and estrous activity increased when animals were moved into pens (Mattoni et al., 1988). Similarly, dairy cows moved between paddocks and the milking parlor had increased mounting activity (Williamson et al., 1972b). Beef cows in drylot exhibited estrus sooner following $PGF_{2\alpha}$ than those on pasture, however confinement area did not influence number of mounts received per estrus (Floyd et al., 2009). Pennington (1985) found that 80% of mounts occurred in locations with best footing and least crowding. Concrete surfaces reduce estrous behavior in dairy cows compared with dirt or straw bedding (Rodtian et al., 1996; Vailes and Britt, 1990).

Social factors - Group size, social hierarchy and behavior, number of females simultaneously in estrus, and the presence of bulls can influence estrous behavior. Social factors such as individual libido are highly variable between individuals and can be confounded by pen size or confinement of animals. Cows nearing estrus usually segregate themselves from the herd, stand closer together, and are more active than the rest of the herd (Williamson et al., 1972b). Dominant cows tend to mount others more often, not allowing others to mount them frequently; conversely, passive cows initiate less mounts while allowing cows to mount them with great frequency during estrus (Refsal and Seguin, 1980; Galina et al., 1982). The number of cows in standing estrus simultaneously impacts estrous behavior. Mounting activity and duration of estrus increase as the number of cows in estrus increased in dairy (Hurnik et al., 1975; Helmer and Britt, 1985; Pennington et al., 1985; Walton and King, 1986) and beef (Floyd et al., 2009) cows. The presence of bulls can influence degree of estrous behavior in females. Libido, aggression and social hierarchy among multiple bulls and between cows and bulls can influence behavior. When bulls are introduced to a herd they often spend more time establishing dominance than detecting estrous cows (Orihuela et al., 1983). There is considerable variation in libido and ability to detect estrous between and within breed and age of bulls.

Environmental factors - Seasonal effects on estrous behavior are primarily a function of ambient temperature and factors influencing heat or cold stress on the animal. However, the extent by which temperature and season impact estrous behavior remains debatable. The duration and severity of temperature stress, cattle genetics, management practices and animal insulation factors likely influence estrous behavior during temperature stress. Trimberger (1948) concluded that season did not influence estrous behavior of dairy cows monitored twice daily for estrus. Similarly, increased temperature had no impact on duration of estrus in dairy cows monitored with HeatWatch® (Walker et al., 1996). Many have found heat stress decreases mounting activity (Gangwar et al., 1965; Pennington et al., 1985; White et al., 2002); however its impact on the duration of estrus is debatable. Cows were in estrus longer in summer compared with spring with more mounts received and greater intervals between mounts in winter than spring or summer (White et al., 2002). Pennington et al. (1985) found that dairy cows were estrus longer with increased interval between mounts in hot weather, and cows receive more mounts in cold weather. However, time of ovulation of beef cows relative to onset of estrus was not influenced by season (White et al., 2002). Most studies agree that the influence of season on estrus is complex and often confounded with multiple factors that influence estrous behavior. Management factors such as milking frequency, movement of cows, feeding, and housing, or bedding could contributed the effects of environmental factors on estrous behavior (Pennington et al., 1985; Britt et al., 1986). Willingness of herd mates to mount, rather than physiological effects of temperature on estrous cows, may explain seasonal effects on estrous behavior (White et al., 2002).

Time of day - Time of day effects on estrous behavior are controversial and, similar to seasonal effects, may be confounded with other factors such as management. Estrous behavior or onset of estrus may not be influenced by the time of day (Castellanos et al., 1997; Xu et al., 1998). However, Mattoni et al. (1988) found that 64% of estrous events began during daylight hours in Zebu cows. Mounting behavior was greater in the morning (De Silva et al., 1981; Galina et al., 1982; White et al., 2002) or during darkness (Hall et al., 1959; Williamson et al., 1972b; Hurnik et al., 1975; Esslemont and Bryant, 1976; Hurley et al., 1982; Walton et al., 1987). Increased estrous activity during the night in dairy cows may be a result of animals not being fed, milked, or handled during this time (Esslemont and Bryant, 1976; Hurnik et al., 1975). Pennington et al. (1986) noted decreased estrous activity in Holstein cows during handling, moving and feeding. This is likely not the case in beef cows because they are managed less intensively. Variation in ambient temperature may influence when the greatest estrous activity occurs. Dairy cows were estrus during the warmest hours in cold weather, yet mounting decreased during the hottest daily hours in warm summer months (Pennington et al., 1985).

Detection of estrus

Many methods and tools have been developed to improve accuracy and decrease labor associated with detection of estrus. Much of the research that developed and improved estrous detection methods was conducted with dairy cows; however, growing demand for high quality beef will continue to drive genetic improvement and the use of AI in beef cattle. Accurate estrous detection is essential for efficient reproduction and high milk production (Foote et al., 1975) and accurate detection of estrus and timing of AI are the keys to improving reproductive efficiency (De Silva et al., 1981). Beef producers often cite labor costs and management considerations as the primary reasons not to detect estrus frequently or at all. Thirty-two percent of dairy farms surveyed did not perform estrous detection consistently because of labor constraints (Sprecher et al., 1995).

Visual observation of animal behavior is the conventional method to detect estrus. Several 30 min observations throughout the day detect most cows in estrus, but estrous detection efficiency increased 10 to 20% when observation periods at 1200 and 2400 h were added to morning and evening (0600 and 1800 h) observation periods (Hall et al., 1959). Ninety-one percent of dairy heifers were detected in estrus by one hour visual observations at 0700, 1200, and 1600 h with 90% detected without the 1200 h observation (Donaldson, 1968). Several tools that aid in visual detection of estrus have been developed and studied; a few of these methods include tailhead painting, chin ball markers, scratch off or reservoir patches (Baker, 1965; Lang et al., 1968; Foote, 1975; Pennington and Callahan, 1986; Macmillan et al., 1988;), teaser bulls (Foote, 1975) or androgenized cows (Kiser et al., 1977; Nix et al., 1998), constant video surveillance (King et al., 1976), and electrical resistance of reproductive tract tissues (Leidl and Stolla, 1976; Ezov et al., 1990; Fisher et al., 2008). Various combinations of these detection aids have also been implemented.

Although frequent visual observation with or without detection aids is effective, it is cost prohibitive and impractical in many beef operations. At-Taras and Spahr (2001) stated that estrous detection by visual observation requires high labor costs and tedious work. Farms and ranches continue to increase in size, increasing the demand for time and labor in multiple facets of the operation during the breading season and decreasing the time available to adequately detect estrus. Senger (1994) depicted the ideal estrous detection system that would provide continuous surveillance of cows, accurate and automatic identification of estrous cows, operation for the productive lifetime of the cow, minimal labor requirements and high accuracy in identifying physiologic and/or behavioral events that are highly correlated with ovulation. Continuous observation (24 h per day) is important because cows may initiate estrus during overnight hours not conducive to visual observation. Reducing or eliminating labor associated with estrous detection will make funds available to invest in technology that may improve estrous detection efficiency. Accurate estrous detection should pay for maintenance of systems due to improved fertility to AI. There are several computerized systems currently available that continuously detect estrus without the need for handling or visual observation of cows. These systems evaluate behavioral and/or physiological changes in physical activity, mounting activity, or body temperature.

Dairy cows had increased activity at estrus when monitored with pedometers, a device attached to the leg that records the number of steps the animal takes (Farris, 1954). Cows in estrus were 2- to 4-times more active than anestrous cows (Kiddy, 1977; Lewis and Newman, 1984; Pennington et al., 1986; Redden et al., 1993). The efficiency of estrous detection using pedometers is variable and ranges from 60 to 100% of visual observation (Lehrer et al., 1992). Use of pedometers has been pursued primarily in dairy cattle because devices can be read during milking when cows are accessible. Major limitations of pedometers include a high rate of false-positives, frequent need for replacement, and animals are required to be gathered daily to collect data (Williams et al., 1981; Pulvermacher and Wiersma, 1991; Lehrer et al., 1992).

The HeatWatch® system is a pressure sensitive device mounted in front of the tailhead that records the date, time and duration of mounts received. This device uses radiotelemetry to send data to a computer for interpretation and nearly eliminates the need for visual observation. HeatWatch® is 78 to 100% accurate and 90 to 100% efficient in detecting estrus (Stevenson et al., 1996; Timms et al., 1997; Xu et al., 1998). However, the advantage of this system over other estrous detection methods is debatable. Greene and Borger (1996) found that HeatWatch® detected more estrous cows (88%) than visual observation (66%) while detection rate was similar to visual observation (Rae et al., 1999) and visual observation combined with tail painting (Xu et al., 1998). When cows with HeatWatch® were continuous observation for 28 h, every estrus detected visually was also detected by HeatWatch®, however HeatWatch® detected 18% less mounts than those visually detected (Floyd et al., 2009). The major shortcoming of this system is the need to glue the device to the tailhead of animals. Mount detector patches are subject to being rubbed off under wet conditions or due to shedding of hair. Missing patches increases labor and expense and decreases the efficiency of estrous detection.

Body Temperature at estrus

Vaginal and core body temperature clearly increase at estrus. A small device can be inserted into the vagina that records and transmits vaginal temperature to a computer. Vaginal temperatures increase from 0.6 to 0.9°C for approximately 7 h during estrus (Redden et al., 1993; Kyle et al., 1998). The use of vaginal temperature for estrous detection was more sensitive but had more false positives than frequent visual observation (Kyle et al., 1998). Radden et al. (1993) found a vaginal temperature system was similar to using pedometers but more effective than visual observation. Maximum vaginal temperature was correlated with the time of the LH peak ($r = 0.83$) and time of ovulation ($r = 0.74$; Rajamahendran et al., 1989). When using elevated vaginal temperature ≥ 0.3°C above the mean for the previous 4 d as criterion, 17 of 21 (81%) estrous cows were identified with 3 false positives (Redden et al., 1993). Similarly, when using a vaginal temperature increase ≥ 0.3°C above the previous 3 d, 7 of 9 estruses were detected with false positives not evaluated (Mosher et al., 1990). Vaginal temperature increased at least 0.3°C during estrus compared with mean vaginal temperature for 3 to 4 d preceding the estrus (Clapper et al., 1990; Mosher et al., 1990; Kyle et al., 1998). Vaginal temperature appears to be a reliable method of estrous detection that warrants further investigation. This system requires attention to maintain the device in correct position within the vagina to prevent irritation and/or infection. Further research should be conducted with vaginal temperature systems to evaluate device durability and factors that may influence accuracy such as season, ambient temperature and health status. Body temperature of cows measured by rectal temperature increased about 1.3°C on the day of estrus, with small seasonal variation (Piccione et al., 2003). Zartman and Dealba (1982), Zartman et al. (1983), and Clapper et al. (1990) all indicated elevated core body temperature at estrus with different devices and methods. Rumen boluses have been developed to determine and record rumen temperatures (Dye, 2007). Boluses are inserted into the reticulo-rumen of cows with a balling gun and are easily removed at the time of slaughter. Rumen temperature boluses use radiotelemetry, much like vaginal temperature and HeatWatch® systems, to send data to a computer for interpretation. Rectal temperature was positively correlated ($r = 0.80$) with rumen temperature in beef steers (Dye, 2007). Rumen boluses allow body temperature evaluation with great frequency and minimal impact on animal behavior, and may be a useful method to detect estrus.

Many factors may influence body temperature at estrus including physical activity, water consumption, feed intake and endocrine secretions. Cows in estrus have increased physical activity (Kiddy, 1977; Pennington et al., 1986) and decreased water consumption (Lukas et al., 2008). Feed intake and water consumption are major contributors to variation in rumen temperature. The magnitude and duration of the decline in rumen temperature depends on volume and temperature of water consumed (Brod et al., 1982; Dye, 2007; Bewley et al., 2008). Diurnal variation in rumen temperature was reported in beef steers (Dye, 2007), dairy cows (Ipema et al., 2008) and beef cows (Prado, 2009) and is likely influenced by feeding methods/frequency, diet, water consumption patterns, animal behavior and management.

Endocrine changes around estrus may impact body temperature of cows (Wrenn et al., 1958). Injection of cattle with estradiol-17β increased vaginal thermal conductance, likely due to increased vaginal blood flow (Abrams et al., 1972; Gwazdauskas et al., 1974). Cows increased vaginal thermal conductance 4 to 5 d before estrus, reached a peak between day -2 and -1, and decreased vaginal thermal conductance by day 0 (onset; Abrams et al., 1975). Changes in vaginal thermal conductance at estrus may be indirectly associated with estradiol secretions (Abrams et al., 1975). Uterine blood flow increased in ovariectomized dairy cows when treated with estradiol-17β (Roman-Ponce et al., 1983). Increases in uterine blood flow during 4 d before to 1 d after estrus were positively associated with estradiol and estrone to progesterone concentrations and negatively associated with concentrations of progesterone in plasma of sheep (Roman-Ponce et al., 1978). Changes in plasma concentrations of estradiol and blood flow at estrus may influence RuT at estrus. Plasma concentrations of estradiol are associated with the ovulatory surge of LH in beef cows (Wettemann et al., 1972) and are greatest on the day of estrus (Stevensen et al., 1998; White et al., 2002). A positive relationship has been established between body temperature increases relative to the time of the surge of LH (Rajamahendran et al., 1989; Clapper et al., 1990; Mosher et al., 1990; Fisher et al., 2008).

The effect of ambient temperature on body temperature variation is unclear. When cattle are within the thermoneutral zone, body temperature remains relatively constant. Ambient temperatures likely have minimal effect on body temperature unless cows are exposed to very hot or cold temperatures (Zartman and Dealba, 1982). Animal body temperature measured with a surgically implanted device increased when ambient temperature decreased, possibly due to changes in thyroxine secretions several days after the ambient temperature change (Zartman and Dealba, 1982). Conversely, Lewis and Newman (1984) found that ambient temperature had a greater impact on vaginal temperature measured only once daily than did the stage of the estrous cycle. The effects of ambient temperature on rumen temperature at estrus have not been established.

The most successful estrous detection systems must be accurate and effective, economical, user friendly, and directly contribute to profitability (Senger, 1994). Multiple devices have been developed to quantify body temperature at estrus, yet a practical system is currently not available to producers. A successful body temperature system will minimize labor inputs, have acceptable longevity, have little impact on animal behavior, and provide frequent, accurate temperature data. The use of rumen temperature boluses to quantify body temperature and predict estrus warrants further investigation.

CHAPTER III

MAINTENANCE ENERGY REQUIREMENTS AND PHYSIOLOGICAL FUNCTIONS OF MATURE BEEF COWS DURING MID-GESTATION

ABSTRACT: The effects of maintenance energy requirements (MR) on rumen temperature, postnatal calf growth, and concentrations of IGF-I, thyroxine (T_4), glucose and insulin in plasma were determined in spring calving Angus cows (n = 42). Nonlactating cows (4 to 7 yr of age) with a BCS of 4.9 ± 0.1 and BW of 572 ± 8 kg, at 160 ± 5 d of gestation were individually fed a complete diet for 8 wk in amounts to supply MR (Model 1, NRC 1996). After 2 wk, daily feed intake was adjusted weekly according to BW change until constant BW was achieved. Rumen temperature was recorded hourly with rumen boluses (Smart Stock, LLC). Two blood samples were taken on each of two consecutive days after constant BW was achieved and at 62 d after calving. Constant BW was achieved for at least 17 d. Daily MR averaged 90.5 ± 5.3 $\mathrm{Kcal \cdot kg\ BW^{-0.75} \cdot d^{-1}}$. Cows were classified based on MR as low (**LMR**, n = 13; > 0.5 SD less than mean), moderate (**MMR**, n = 11; ± 0.5 SD of mean) or high (**HMR**, n = 8; > 0.5 SD greater than mean). Cows that did not achieve constant BW were excluded from analyses (n = 10). Amount of daily energy required to maintain constant BW and BCS differed ($P < 0.001$) by MR. There was a 29% difference in the amount of energy required for maintenance between the most and least efficient cows. Plasma concentrations of insulin, glucose, and thyroxine were not influenced by MR. During the period when cows maintained constant BW (MR period), concentrations of IGF-I were greater for cows with MMR compared with LMR ($P = 0.02$) and HMR ($P =0.01$) cows. During early lactation, cows with MMR had greater concentrations of IGF-I compared with LMR ($P = 0.01$) and HMR ($P = 0.03$) cows. Calf birth weight ($P = 0.89$), 205 d adjusted weaning weight ($P = 0.58$), and ADG from birth to weaning ($P = 0.58$) were not influenced by MR. Cows with LMR had greater ($P = 0.02$) mean RuT during the MR period compared with HMR cows; RuT of MMR cows did not differ from LMR ($P = 0.15$) or HMR ($P = 0.24$) cows. Plasma concentrations of glucose, thyroxine and insulin were not influenced by MR; however, IGF-I in plasma and RuT were influenced by MR. A combination of biomarkers may identify cows that require less energy to maintain BW. Selection of cows that are more efficient, without influencing performance, could improve efficiency of beef cattle production.

INTRODUCTION

Maintenance energy requirement (MR) of cows is the greatest variable cost in beef production. Approximately 70% of the total energy required by cows and about 45% of the total energy required for beef production is attributed to MR, and this value is independent of cow type (Ferrell and Jenkins, 1984). In addition, feed costs have increased $5 per beef cow per year since 2000 (American Angus Association, 2006).

Efficiency in the cow-calf industry could be improved by decreasing the energy required for maintenance of cows.

Differences in MR within and between breeds have been identified (Ferrell and Jenkins, 1984; DiCostanzo et al., 1990; Derno et al., 2005). Within herd or breed, the CV for MR of beef cattle ranges from 5 to 35% (Johnson et al., 2003; Prado, 2009) and heritability of MR was estimated at 0.52 (Hotovy et al., 1991), indicating an opportunity for improved efficiency through selection. A viable biomarker for selection of efficiency has not been developed for commercial application. Current methods to estimate MR are expensive, time consuming, and require specialized equipment and/or expertise. Future feed efficiency research should focus on methods to assess individual animal differences in efficiency, particularly variation in MR of mature beef cows (Johnson et al., 2003). A practical method to identify individuals with high and low efficiency must be developed to replace costly and time consuming respiration or slaughter methods (Johnson et al., 2003). Identification of more efficient and reliable methods to identify and select beef cows that require less energy for maintenance, while maintaining performance, should increase efficiency of beef cattle production.

Accurate biomarkers that identify individual differences in MR of cows are essential for selection of more energetically efficient cows. Biomarkers must be both accurate and economical to be adopted by beef cattle producers. Metabolic hormones regulate biological processes that contribute to MR. Insulin-like growth factor-I is a protein hormone secreted by the liver and peripheral tissues. Glucose and amino acid metabolism, protein accretion (Jones and Clemmons, 1995) and net protein synthesis (Lobley, 1992) are influenced by IGF-I. Insulin-like growth factor-I has been associated with increased feed efficiency (Bishop et al., 1989; Stick et al., 1998) and has been used as an indirect selection method for residual feed intake (RFI; Davis and Simmen, 2006). Thyroid hormones have a central role in energy homeostasis and body temperature regulation. Plasma concentrations of thyroxine (T_4) are associated with feed intake in cattle (Ciccioli et al., 2003; Lents et al., 2005). Metabolism of carbohydrates, lipids, and proteins are influenced by thyroid hormones (Moreno et al., 2008).

Rectal temperature has been positively associated with MR in mice (Kgwatalala et al., 2004) and steers (Derno et al., 2005). Residual feed intake was positively associated with heat production in steers fed 2.5 x MR. Rumen boluses have been developed to record rumen temperature (Dye, 2007). Rumen boluses allow frequent body temperature evaluation with minimal impact on animal behavior. Plasma concentrations of metabolic hormones and rumen temperature are possible biomarkers for MR of beef cows. Therefore, objectives of this study were (1) to estimate and describe variation in MR of mature beef cows during mid gestation, (2) to determine if cow performance and postnatal calf growth are influenced by amount of energy required for maintenance, (3) and to evaluate the effect of MR of cows on plasma concentrations of IGF-I, T_4, insulin, glucose and rumen temperature.

MATERIALS AND METHODS

Animals and Estimation of Maintenance Energy Requirements

Experimental procedures used in this study were approved by the Oklahoma State University Animal Care and Use Committee. Angus cows (4 to 7 yr of age) were AI to a single Angus sire during 20 d in May. Maintenance energy requirements (MR) were estimated in nonlactating, pregnant cows (n = 42) with a BCS of 4.9 ± 0.1, and BW of 572 ± 8 kg during 6 to 7 mo of gestation (November and December).

The NRC (1996) defines MR as the amount of dietary energy intake that results in no net loss or gain of energy from animal tissues. To estimate actual MR, cows were individually fed once daily at 0730 h a complete diet consisting of (as fed) dry rolled corn (36%), alfalfa pellets (35%), cottonseed hulls (22%), soybean meal (4%), cane molasses (3%), salt (0.2%) and vitamin A (0.01%). Calculated (NRC, 1996) CP and NE_m for the diet were 11.2% and 1.43 Mcal/kg, respectively. The total mixed ration was sampled weekly and ground for nutrient analysis using a Wiley mill with a 2 mm screen. Near infrared reflectance spectroscopy (NIR) was performed (Dairy One Laboratory, Inc., Ithaca, NY) on four samples taken during the MR feeding period. Mean analyzed values (as fed) for CP and NE_m were 13.0% and 1.41 Mcal/kg, respectively, and were similar to pre-trial calculated values. A mineral supplement (46.1% NaCl, 50.0% dicalcium phosphate, 0.4% copper sulfate, 0.5% zinc oxide and 3.0% mineral oil) and fresh water were supplied to cows ad libitum.

Cows were fed diets to meet their MR based on the NRC Table Generator Software of the Level 1 Model (NRC, 1996). Initial BW for each cow was used to calculate MR. Shrunk body weights, after deprivation from feed (23 h) and water (17 h), were recorded at the initiation of the trial, weekly during the first 4 wk of the feeding period, and twice weekly during the final 3 wk of the feeding period. Body condition score (1 = emaciated, 9 = obese; Wagner et al., 1988) was determined at the beginning and end of the MR feeding period. Body weight and BCS of cows after 15 h deprivation of feed and water were recorded at 244 ± 5 d of gestation, 41 ± 6 d after calving, and at weaning. Calf BW was recorded at birth (mean calving date = March 5), early lactation (62 ± 6 d), mid-lactation (146 ± 6 d), and at weaning (210 ± 6 d).

After cows consumed diets to meet NRC predicted MR for 14 d, daily feed offerings were adjusted every 7 d, if necessary, to maintain constant BW. When BW of a cow increased or decreased 14 kg over 3 consecutive weights, the ration was decreased or increased by 0.45 kg feed/d (as fed) compared with the previous intake. Diet refusal ($\geq$ 2 kg) only occurred for one cow on 2 d before the period when intake was used to calculate MR. Actual MR of cows was determined during the same 17 d when all cows had achieved constant BW. Constant BW was determined with regression analyses using PROC REG (SAS Institute Inc., Cary, NC). Cows with a significant linear regression ($P < 0.10$) of BW over days (n = 10) were eliminated from further analyses.

Dietary energy required to maintain constant BW (MR) was expressed as Kcal·kg $BW^{-0.75} \cdot d^{-1}$. Final MR was calculated using mean constant BW and daily energy (NE_m) consumed during the 17 d constant BW period. Cows were classified based on MR as low (**LMR**, n = 13; > 0.5 SD less than mean), moderate (**MMR**, n = 11; ± 0.5 SD of mean) or high (**HMR**, n = 8; > 0.5 SD greater than mean). Cows that lost calves at birth or in early lactation were excluded from further analyses (n = 2; 1 LMR and 1 MMR).

After MR of each cow was determined (Dec 24), cows were managed as a group with ad libitum native range (*Andropogon scoparius, Andropogon gerardii*) pasture (60 hectares). Cows were fed 1.4 kg of a 38% CP supplement during late gestation and 1.8 kg of a 38% CP supplement during early lactation until adequate forage in the spring. Calf birth weights and gestation lengths were recorded and calves remained with cows until weaning (209 ± 3 d of age).

Blood samples and analyses

Blood was collected from the tail vein during the period when cows consumed actual MR diets (MR period), and during early lactation (62 d post partum). All cows were sampled at 0700 and 1500 on two consecutive days during both periods. During the MR period, cows were deprived of water for 17 h and feed for 23 h before the 0700 samples. Cows were fed at 0730 and had ad libitum water between morning and afternoon samples. In early lactation, cows were sampled at 0700 directly after removal from native range pasture and access to water. Cows were maintained in drylot without access to feed or water between collection of samples at 0700 and 1500 and grazed native range pasture between samples at 1500 on the first day and 0700 on the second day. Samples were collected into Monoject™ blood collection tubes containing EDTA (Tyco Healthcare Group, LP), stored on ice, and centrifuged at 2,500 g for 20 min at 4°C within 2 h after collection. Plasma was aspirated and stored at -20°C until analyzed.

Samples were assigned to assay blocks by MR and cow, such that each block had a similar number of cows for each MR (LMR, MMR, and HMR) and all samples for a cow were included in one assay. Concentrations of IGF-I in plasma were determined by RIA after acid ethanol extraction (Echternkamp et al., 1990). Samples were analyzed in two blocks for both the MR and early lactation sample periods. Intra and interassay CV (n = 4 assays) were 7 and 14%, respectively. Plasma concentrations of glucose during the MR period were quantified with an enzymatic colorimetric procedure (Thermo DMA, Louisville, CO) in 10 assays. Intra and interassay CV (n = 10 assays) were 2 and 4%, respectively. Concentrations of insulin in plasma during the MR period (1 assay) and early lactation (1 assay) were quantified with a solid phase RIA (Coat-A-Count Insulin kit, Diagnostic Products Corp., Las Angeles, CA) for human insulin (Bossis et al., 1999) with bovine pancreatic insulin as the standard (Sigma Chemical Co., St. Louis, MO). The intraassay CV (n = 2 assays) was 5%. Plasma concentrations of thyroxine (T_4) were quantified (MR period = 6 assays; early lactation = 5 assays) with a solid phase RIA (Coat-A-Count Total T_4 kit, Diagnostic Products Corp.) designed to quantify total T_4 in plasma (Ciccioli et al., 2003). Intra and inter assay CV (n = 11 assays) were 5 and 8%, respectively.

Rumen Temperature

Rumen temperature (RuT) boluses (8.25 cm x 3.17 cm; 114 g) with individual identification numbers were placed into the reticulo-rumen of each cow with a custom balling gun. A data recovery system (SmartStock®, LLC, Pawnee, OK) was installed at the South Range Cow Research Center to collect RuT. Two data collection antennas on the perimeter fence of the pen, where cows were maintained (60 x 80 m), collected and transmitted RuT data hourly from each bolus. Each RuT recording also included hourly temperatures for the previous 12 h. Information was relayed from data collection antennas to a receiver antenna at the office. Data collection and receiver antennas were within 100 m of the cows. Rumen temperature, time, date and cow identification were transmitted hourly to a computer equipped with software compatible with the RuT collection system (SmartStock®, LLC).

Statistical analyses

Cow and calf BW and cow BCS were analyzed as a completely randomized design with the GLM procedure of SAS (SAS Institute Inc., Cary, NC). Maintenance requirement, calf sex and the interaction were included in the statistical model for calf data. Maintenance energy requirement of cows was analyzed with the GLM procedure of SAS (SAS Institute, Inc.). The statistical model included MR group (LMR, MMR, HMR) and energy consumed during the MR period (Kcal·kg $BW^{-0.75}·d^{-1}$). When effects were significant, least squares means (LSM) were compared using LSD (pdiff) of SAS.

Concentrations of hormones in plasma during the MR period and early lactation were analyzed separately with the MIXED procedure of SAS using a completely randomized design. The statistical models for IGF-I, insulin, glucose, and T_4 included MR, hour, block (laboratory assay, if more than one) and the interactions. All effects in the model were fixed except block, which was treated as a random effect. Six covariance structures (variance component, compound symmetry, Huynh-Feldt, first-order autoregressive, Toepliz and unstructured) were considered to identify the best structure for data according to the goodness of fit statistics. Variance components for all analyses were estimated using the restricted maximum-likelihood method. The covariance structures with the best goodness of fit statistics for each hormone were: Huynh-Feldt for insulin (MR period and early lactation) and T_4 (early lactation); compound symmetry for glucose (MR period) and T_4 (MR period); TOEP for IGF-I (MR period); and unstructured for IGF-I (early lactation). Denominator degrees of freedom were determined using the Kenward-Roger procedure.   Interactions that were non-significant ($P > 0.30$) were deleted from the final model. When treatment effects were significant ($P < 0.05$), least squares means were compared using LSD (pdiff) of SAS.

Rumen Temperature (RuT) was analyzed using the MIXED procedure of SAS. A mean daily RuT was calculated for each cow during four consecutive days (Dec 20 to 23) during the MR period, and during two consecutive days (May 19 and 20) in early lactation (68 d after calving). To be considered for evaluation, at least 5 RuT readings were required for a cow each day. Means were calculated for 24 h during both MR and early lactation periods. Means were also calculated for 20 h (excluding daily h 0900 through 1200) during both MR and early lactation periods to reduce diurnal variation (Figure 1). Values < 37.72°C were excluded from analyses to reduce variation associated with water and feed consumption (Dye, 2007; Prado, 2009). Rumen temperatures were normally distributed and excluding values < 37.72°C reduced skewness and variance. The initial statistical model included MR, date, and the interaction, with mean daily ambient temperature (Oklahoma Mesonet, Marena Station) included as a covariable. Effects that were not significant ($P > 0.30$) were eliminated from the final model. Similar to analyses of hormones, six covariance structures were evaluated to select the appropriate structure. The covariance structure with the best goodness of fit for all RuT data was compound symmetry. When effects were significant ($P < 0.05$) LSM were compared using LSD (pdiff) of SAS. Spearman's coefficient of ranked correlation was determined for MR and RuT during the MR period and early lactation using PROC CORR.

RESULTS

The complete diet was fed for 7 wk and the average duration that cows were at constant BW and BCS was 31 d (46 d, n = 12; 25 d, n = 11; 17 d, n = 9). Mean daily ambient temperature during the period when cows consumed actual MR diets (MR period, Dec 7 to 24) was 2 ± 4°C. Minimum and maximum daily ambient temperatures during the MR period averaged -4 ± 3°C and 7 ± 7°C, respectively. Ambient temperature ranged from -9°C to 20°C during the MR period.

Mean MR (NE_m) was 90.9 ± 5.3 Kcal·kg BW $^{-0.75}\cdot d^{-1}$ with a CV of 5.9%. The difference between the cow with the greatest and least MR was 29% (Figure 2). The actual amount of energy required to maintain constant BW was influenced ($P < 0.001$) by MR classification (Table 1).

Body weight of cows was not influenced ($P \geq 0.35$) by MR (Table 2) and was 572 ± 8 kg at the start of the trial and 569 ± 8 kg on the final day when cows were fed actual MR. Cows weighed 624 ± 8 kg at 244 ± 5 d of gestation, 537 ± 13 kg at 62 ± 6 d after calving and 603 ± 11 kg at weaning (Figure 3). Initial (4.9 ± 0.1) and final (5.0 ± 0.1) BCS of cows were not influenced ($P \geq 0.16$) by MR (Table 3). There was a tendency for MR to influence BCS at 244 d of gestation ($P = 0.09$) and at 41 d after calving ($P = 0.08$). At 244 ± 5 d of gestation, cows with HMR had less BCS ($P = 0.04$) compared with MMR cows and tended ($P = 0.06$) to have less BCS compared with LMR cows; BCS of MMR and LMR cows were similar ($P = 0.78$). At 41 ± 6 d after calving, HMR cows had less BCS ($P = 0.02$) compared with MMR cows; BCS was not different for HMR and LMR cows ($P = 0.24$) and LMR and MMR cows ($P = 0.19$). Body condition of cows was not influenced by MR at 62 ± 6 d ($P = 0.17$) or 146 ± 4 d ($P = 0.35$) after calving or at weaning ($P = 0.74$).

Body weight of calves were not influenced by calf sex ($P > 0.28$) or MR x calf sex ($P > 0.16$). Birth weight (38.9 ± 0.8 kg; $P = 0.89$) and 205 d adjusted weaning weight (201.3 ± 4.3 kg; $P = 0.58$) of calves were not influenced by MR (Table 4). Calf age at weaning (209 ± 3 d) was not influenced (*P* = 0.75) by MR. Average daily gain of calves from birth to weaning (0.98 ± 0.10 kg) was not influenced by MR (*P* = 0.58).

Sample (*P* = 0.50) and MR x sample (*P* = 0.57) did not influence plasma concentrations of IGF-I (Table 5) when cows were consuming actual MR (MR period). Concentrations of IGF-I during the MR period were influenced by MR (*P* = 0.03; Figure 4). Concentrations of IGF-I were greater for cows with MMR compared with LMR (*P* = 0.02) and HMR (*P* = 0.01); LMR and HMR cows had similar concentrations of IGF-I (*P* = 0.58) during the MR period. There was no MR x sample effect (*P* = 0.82) on plasma concentrations of IGF-I during early lactation (62 ± 6 d), and IGF-I was influenced by MR (*P* = 0.03; Figure 5). Cows in the MMR group had greater concentrations of IGF-I compared with LMR (*P* = 0.01) and HMR (*P* = 0.03) cows. Concentrations of IGF-I were similar (*P* = 0.93) for LMR and HMR cows during early lactation. Plasma concentrations of IGF-I were influenced (*P* = 0.003) by sample in early lactation (Table 5) with greater concentrations in sample 1 on day 1 and both samples on day 2 compared with sample 2 on day 1.

Concentrations of glucose were not influenced by MR x sample (*P* = 0.25; Table 5). Maintenance energy requirement of cows did not influence (*P* = 0.69) concentrations of glucose in plasma (Table 6). Sample tended to influence (*P* = 0.08) concentrations of glucose in plasma during the MR period (Table 5); concentrations were greatest in sample 1 on days 1 and 2 (*P* <0.01), and least in sample 2 on day 1. Concentration of glucose in sample 2 on day 2 was not different from the other samples (P ≥ 0.62).

There were no MR x sample (*P* = 0.14) or sample (*P* = 0.57) effects on concentrations of insulin in plasma during the MR period (Table 5). Concentrations of insulin in plasma were not influenced by MR during the MR period ($P = 0.22$; Table 6). There was no MR x sample ($P = 0.86$) effect on concentrations of insulin in plasma during early lactation. Concentrations of insulin were not influenced by MR during early lactation ($P = 0.13$). Concentrations of insulin during early lactation were influenced by sample ($P < 0.001$) with greatest concentrations in sample 1 on day 1 and 2 ($P < 0.01$), and least in sample 2 on day 1 (Table 6). Concentration of insulin in sample 2 on day 2 was not different from the other samples ($P \geq 0.84$).

Plasma concentrations of T_4 were not influenced by MR x sample during the MR period ($P = 0.34$) or early lactation ($P = 0.12$; Table 5). Concentrations of T_4 in plasma were not influenced by MR (Table 6) during the MR period ($P = 0.86$) or early lactation ($P = 0.21$). There was no sample effect on plasma concentrations of T_4 during the MR period ($P = 0.66$; Table 5). Time of sample influenced concentrations of T_4 during early lactation ($P < 0.001$) with greater concentrations in sample 2 on day 2 compared with the other samples ($P < 0.001$). Concentrations of T_4 in samples 1 and 2 on day 1 and sample 1 on day 2 were similar ($P \geq 0.77$).

There was diurnal variation in RuT of cows (Figure 6); therefore, RuT was analyzed for all values during 24 h and for 20 h after deleting values from 0900 through 1200. There was a MR x date effect ($P = 0.04$) on RuT when evaluating all daily hours during the MR period; however, this was a result of differences in magnitude rather than direction of the response (Figure 7). Mean RuT was influenced by MR ($P = 0.05$) when evaluating all daily hours from Dec 20 to 24 (Table 7). Cows in the LMR group had greater ($P = 0.02$) mean RuT during the MR period than HMR cows when all daily hours were analyzed. Rumen temperature of MMR cows did not differ from LMR ($P = 0.15$)

or HMR ($P = 0.24$) cows. Mean daily ambient temperature did not influence RuT ($P = 0.78$); however, there was a date effect ($P < 0.001$) on RuT (Table 8). Mean RuT on day 3 (Dec 22, 38.31°C) was greater ($P \leq 0.04$) than RuT on day 1 (Dec 20, 38.22°C), day 2 (Dec 22, 38.18°C) and day 4 (Dec 23, 38.17°C).

There was a MR x date effect ($P = 0.05$) on RuT when daily hours 0900 through 1200 were deleted (20 h per day analyzed during the MR period), however this was a result of differences in magnitude rather than direction of the response (Figure 7). Mean RuT tended to differ by MR ($P = 0.09$) when daily hours 0900 through 1200 were deleted (Table 8). Cows in the LMR group had greater ($P = 0.03$) mean RuT during the MR period than HMR cows; MMR cows did not differ in RuT compared with LMR ($P = 0.16$) or HMR ($P = 0.37$) cows. Mean daily ambient temperature did not influence RuT ($P = 0.41$), however there was a date effect ($P < 0.006$) on RuT (Table 8). Mean RuT was greatest on day 3 (Dec 22, 38.28°C) and least on day 4 ($P < 0.001$; Dec 23, 38.15°C). Rumen temperatures on day 1 (Dec 20, 38.20°C) and day 2 (Dec 21, 38.19°C) were not different from RuT on day 3 or day 4 ($P \geq 0.67$). Mean RuT during the constant BW period was not correlated (-0.28; $P = 0.13$) with MR (Kcal·kg BW$^{-0.75}$·d^{-1}) of cows (n = 30).

There were no MR x date ($P = 0.38$) or date ($P = 0.53$) effects on RuT when evaluating all hours on two consecutive days (May 19 and 20) during early lactation (68 d after calving). Mean RuT was not influenced by MR ($P = 0.40$) during early lactation (Table 7). Mean daily ambient temperature did not influence RuT ($P = 0.52$) when evaluating all daily hours on two consecutive days.

There were no MR x date (*P* = 0.13) or date (*P* = 0.34) effects on RuT when daily hours 0900 through 1200 were deleted (20 h per day analyzed) on two consecutive days (May 19 and 20) during early lactation (68 d after calving). Mean RuT was not influenced by MR (*P* = 0.31) during early lactation (Table 7). Mean daily ambient temperature did not influence RuT (*P* = 0.59) when evaluating all daily hours on two consecutive days. Mean RuT during early lactation was not correlated (-0.37; P = 0.22) with MR (Kcal·kg BW $^{-0.75}$·d^{-1}) of cows (n = 13).

Discussion

Maintenance energy requirements averaged 90.9 ± 5.3 Kcal·kg BW$^{0.75}$·d. Previous trials in our lab with a similar model yielded mean MR of 89.2 and 93.0 Kcal·kg BW $^{-0.75}$·d^{-1} (Prado, 2009). Maintenance energy requirements for mature, nonlactating, nonpregnant Angus cows have been estimated between 91.4 and 156.7 Kcal·kg BW$^{0.75}$·d (Ferrell and Jenkins, 1985; Solis et al., 1988; DiCostanzo et al., 1990; Laurenz et al., 1991). Other studies showed that daily NE$_m$ for mature, nonlactating, nonpregnant Angus x Hereford cows ranged from 127 to 151 Kcal·BW$^{0.75}$·d (Thompson et al., 1983; Ferrell and Jenkins, 1985; Reid et al., 1991). Mean estimated MR for mature cows based on the average BW (567 kg) at maintenance is 77 Kcal·kg BW$^{0.75}$·d (NRC, 1996, Level 1 Model). The NRC estimated value is lower than actual energy consumed by cows to meet maintenance requirements in this experiment. Maintenance requirements are computed by the Level 1 model by adjusting the base NE$_m$ required for breed, physiological state, activity and heat loss vs. heat production (computed from ME intake and retained energy). Heat loss is affected by animal insulation factors and environmental conditions (NRC, 1996). Environmental conditions were set to thermoneutral for NRC estimated calculations. The Level 1 model was developed based on prediction equations as a tool for predicting and evaluating requirements from diets fed across a wide variety of objectives, cattle types, physiological states, and environmental conditions. Field experience and animal performance records should be used to strengthen predicted requirements. Differences in physiological and environmental conditions, specific methods used to estimate MR, and other variables may explain differences in estimated MR among studies.

The difference between the cow with the greatest and least MR was 29%. Previous trials in our lab with a similar model found differences of 29% and 24% (Prado, 2009b). Similarly, MEm varied by 27% in Angus cows (DiCostanzo et al., 1990) and 23% in Hereford steers (Derno et al., 2005). The coefficient of variation (CV) for MR in this study was 5.9%. Previous trials in our lab with a similar model showed a CV of 7% and 5% (Prado, 2009), and the CV for MR in Angus cows was 11% (DiCostanzo et al., 1990). These studies support the concept that variation in MR exists within a herd of similar cows. Differences in MR among cows may be expressed relative to each other across different physiological states (Ferrell and Jenkins, 1985a; Montano-Bermudez et al., 1990) and seasons (Laurenz et al., 1991). After 15 generations of selection for heat loss in mice, Neilsen et al. (1997) observed heritability for heat loss was between 0.25 and 0.30. Maintenance requirements are moderately heritable ($h^2 = 0.52$) in beef cattle (Hotovy et al., 1991). Similarly, residual feed intake (RFI), a measure of feed efficiency, is moderately heritable in cattle (Arthur et al., 2001), ranging from 0.28 to 0.58 (Koch et al., 1963; Crews et al., 2003). These studies indicate that variation in MR exist and heritability of MR may allow for selection of more efficient beef cows.

Prior and Laster (1979) found maximum calf fetal weight gain (352 g/day) occurred at 232 d of gestation. Cows in this study were at 206 ± 5 d of gestation on the final day of the MR feeding period and all cows calved within 25 d. Weight gain due to fetal growth during determination of MR accounted for only less than 2% of maternal BW and was similar for all cows.

Body weight of cows was similar throughout the trial, indicating that LMR cows are more efficient in utilization of energy compared with contemporaries. In addition, MR tended to influence BCS of cows at 244 d of gestation and 41 d after calving; HMR cows had less body condition compared with MMR and LMR cows. Cows with greater MR may have been in a greater negative energy balance during late gestation and early lactation, and consequently mobilized more fat stores compared with moderate and low MR cows. Body condition score at parturition influences onset of luteal activity and the duration of postpartum anestrus. Cows in moderate condition at parturition had a shorter postpartum anestrus compared with thinner BCS cows (Richards et al., 1986). Pregnancy rates were greater for cows in moderate compared with thin BCS at parturition (Lents et al., 2008). Cows with less BCS at parturition are less fertile at the first estrus postpartum compared with cows in moderate body condition (Ciccioli et al., 2003). Days to resumption of luteal activity post partum were not influenced by MR of cows in previous years with a similar experimental model (Prado, 2009). Mean BCS for HMR cows were not less than 4.0 during early lactation. When BCS is less than 4, postpartum cows do not initiate estrous cycles until body condition improves or until days after calving increases (Richards et al., 1986; Bishop et al., 1994; Wettemann et al., 2003). Although differences were detected, BCS did not drastically differ between MR groups. These results indicate that selection for cows with less MR will likely not negatively impact postpartum resumption of luteal activity and subsequent reproduction. Additionally, HMR cows may be at risk for reduced postpartum reproductive performance because of reduced BCS, especially when energy is limited by reduced forage availability during early lactation. Selection of heifers for low RFI did not influence subsequent reproductive performance when compared with heifers with greater RFI (Arthur et al., 2005; Lancaster, 2008a). Future research should be devoted to better understanding the effects of MR on reproductive performance.

Birth weight and 205 d adjusted weaning weight of calves were not influenced by MR in this study. Maternal milk production is associated with weaning weights of calves (Neville, 1962; Rutledge et al., 1971). This indicates that milk production was not influenced by MR in the present study. Milk production potential was not influenced by feed intake in Herford x Angus, Herford x Simmental, and Hereford x Tarentaise cows; cows consuming less energy relative to milk production were most efficient (Freking and Marshall, 1992). Although milk production was positively associated with MR in different breeds and types of cows (Ferrell and Jenkins, 1984), only 23% of the variation in MR was explained by differences in milk production (Montano-Bermudez et al., 1990). Milk production was likely not associated with MR in the present study, since weaning weights of calves from dams with low, moderate, or high MR were similar.

Concentrations of IGF-I in plasma were greater in MMR cows compared with low and high MR cows during both the MR period and early lactation. Insulin-like growth factor-I is largely produced by the liver in response to growth hormone (Jones and Clemmons, 1995; Keisler and Lucy, 1996). Cattle that are in a negative energy balance have increased plasma concentrations of GH and decreased plasma concentrations of IGF-I (Reynolds et al., 1991; Keisler and Lucy, 1996; Bossis et al., 1999). Receptors for GH in the liver and plasma IGF-I are positively associated with nutrient uptake (Donaghy and Baxter, 1996). Concentrations of IGF-I in plasma are associated with increased feed efficiency (Bishop et al., 1989; Stick et al., 1998) and have been used as an indirect selection method for RFI (Davis and Simmen, 2006). IGF-I has been used in Australia and the United States to select for feed efficiency; however, the relationship between RFI and IGF-I is not clear due to conflicting results (Moore et al., 2009). Some studies have identified positive correlations between IGF-I and feed efficiency (Moore et al., 2005), while others have found a minimal or no correlation (Lancaster et al., 2008b). The relationship between concentrations of IGF-I and RFI may be influenced by composition of growth and age at time of sampling (Lancaster et al., 2008b). The reliability of IGF-I as a biomarker for selection of efficient animals, and the extent of the relationship between IGF-I and RFI is currently in question. Additional research will be necessary to determine if IGF-I can be used for selection of more efficient cattle (Moore et al., 2009). Concentrations of IGF-I in the current study were influenced by MR; however, results are difficult to explain because MMR cows had greater concentrations of IGF-I than HMR and LMR cows. Additional research is necessary to determine the relationship between concentrations of IGF-I and MR.

During early lactation, plasma concentrations of IGF-I were influenced by sample hour with greater concentrations in sample 1 on day 1 (0700) and day 2 (0700) and sample 2 on day 2 (1500) compared with sample 2 on day 1 (1500). Animals were maintained in a drylot without access to feed or water between 0700 and 1500 daily. Similarly, gestating beef cows had greater concentrations of IGF-I in plasma after restricted from water and feed for 18 h compared with samples taken 1 h after feeding (Lents et al., 2005). Concentrations of GH in plasma tended to decrease after feeding dairy cows (Sutton et al., 1988), which may be a result of greater IGF-I concentrations in plasma and the negative feedback of IGF-I on secretion of GH. Differences in plasma concentrations of IGF-I exist among breed and type of cow, physiological state, diet, and frequency of feeding.

Concentrations of insulin and glucose in plasma were not influenced by MR. Concentrations of insulin in cows during early lactation were influenced by hour of sample. Insulin was greater in samples obtained directly after removal of cows from native range pasture (0700 h) compared with samples taken after cows were maintained in drylot without access to feed or water for 7 h (1500 h). Concentrations of insulin were not influenced by hour of sample during the MR period. However, hour of sample tended to influence concentrations of glucose during the MR period ($P = 0.08$); concentrations of glucose were greatest in sample 1 on day 1(0700) and day 2 ($P < 0.01$; 0700), intermediate in sample 2 on day 2 (1500) and least in sample 2 on day 1 (1500). Changes in concentrations of insulin in plasma usually correspond to changes in plasma glucose (Richards et al., 1989b). Insulin in plasma increased 1 h after feeding beef cows (Lake et al., 2005), and 3 to 5 h after feeding dairy cows (Sutton et al., 1988). Concentrations of insulin in plasma of pregnant beef cows were greater after feed and water were restricted for 18 h compared with samples from fed cows (Lents et al., 2005).

Plasma concentrations of glucose and secretion of insulin and glucose are influenced by composition of the diet fed, feed intake relative to sampling, and other management practices.

Concentrations of T_4 in plasma were not influenced by MR of cows. Thyroid hormone has a central role in energy homeostasis and regulation of body temperature. Plasma concentrations of T_4 are associated with feed intake (Richards et al., 1995; Ciccioli et al., 2003). Kgwatalala (2004) detected no differences in serum T_3 or T_4 concentrations of mice divergently selected for heat loss. Conversely, T_4 was greater in low-producing (milk) dairy heifers compared with high-producing heifers (Bitman et al., 1984). Plasma concentrations of T_4 were not influenced by hour of sample during the MR period. During early lactation, plasma concentrations of T_4 were greater at sample 2 on day 2 (1500) compared with the three previous samples. Similarly, plasma concentrations of T_4 in pregnant dairy heifers were least in morning hours and increased throughout the day (Bitman et al., 1984).

Cows may have been sampled too infrequently to detect differences in insulin and T_4. Frequent samples with jugular canulated animals and/or performing a glucose tolerance procedure may elucidate possible differences in the efficiency of glucose uptake by cells and/or insulin secretion in cows with different MR. Although T_4 is the primary form of iodothyronine secreted by the thyroid, triiodothyronine (T_3) is the major active form at the receptor in cells (Heuer and Visser, 2009). Total plasma T_4 concentrations were measured in this study. Thyroid hormone-binding proteins (specifically TBG) in plasma influence the availability of thyroid hormone to cells. Further investigation of the role that thyroid hormone has in MR should be pursued.

Concentrations of IGF-I, T_4, glucose and insulin may not be beneficial as individual biomarkers for MR; however, these hormones may be combined in a predictive model for MR. Further investigation of the relationships of these and other hormones and metabolites as biomarkers is warranted.

When evaluating all daily hours for four consecutive days during the MR period, LMR cows had greater mean RuT than HMR cows, and RuT of MMR cows was intermediate. Cows in the LMR group consumed less feed on both an as fed and energy basis. We hypothesize that less feed intake results in less heat of fermentation in the rumen, causing a decrease in water consumption, and therefore greater mean RuT for LMR cows. In contrast, HMR cows with greater feed intake may consume more water to dissipate heat associated with rumen fermentation, decreasing mean RuT. Additionally, differences in RuT may be explained by differences in heat dissipation that are unrelated to water consumption. Cows that differ in MR may produce similar amounts of heat. If LMR cows are less efficient at dissipating heat compared with HMR cows, greater core body temperature may contribute to increases in RuT in LMR cows. Further investigation of the roles of feed and water consumption and animal behavior on RuT should be pursued. A better understanding of the relationship between RuT and core body temperature relative to feeding, activity, and physiological state will be beneficial to determine possible relationships between RuT and MR.

The effect of MR on RuT was also evaluated by deleting daily hours 0900 through 1200 (20 h per day analyzed) during the MR period. This analysis was developed to reduce variation in RuT associated with diurnal variation. Rumen temperature changed drastically during morning hours associated with feed and water consumption (Figure 6). Cows were fed once daily at 0730 and water consumption was observed for many cows directly after feeding. Without eliminating morning hours it may be difficult to detect small differences in RuT without directly measuring the quantity and precise timing of both feed and water consumption.

Rectal temperatures were positively associated with MR of beef steers ($r = 0.70$, $P = 0.06$; Derno et al., 2005) and mice (Mousel et al., 2001; Kgwatalala et al., 2004). Core body temperature averaged 0.51°C greater ($P < 0.01$) in mice selected for high (less efficient) heat loss compared with mice selected for low (more efficient) heat loss (Mousel et al., 2001). Variation in heat loss is the primary contributing factor to variation in core body temperature (Refinetti and Menaker, 1992). Heat production/loss in non-growing animals is highly correlated with feed intake and MR (Nielsen et al., 1997). Heat production is greater in growing cattle with high RFI compared with low RFI (Basarb et al., 2003). Metabolizable energy that is not utilized or stored in body tissues is lost as heat; therefore, animals that are more efficient will convert greater proportions of ME into tissue rather than heat production, compared with less efficient animals.

Mean daily ambient temperature did not influence RuT yet mean RuT was influenced by date. Core body temperature of mice was influenced by day of collection despite no change in environmental chamber conditions (Mousel et al., 2001). Ambient temperature may be important to consider when developing a model to predict onset of estrus and MR with RuT. Future attention should focus to better understanding the roles of ambient temperature, feed and water consumption, animal behavior, and other environmental factors on RuT, as well as the relationships among RuT, core body temperature, and heat production.

Residual feed intake (RFI) is a measure of feed efficiency that is strongly related to DMI, but is independent of level of production (growth) and mature size (Herd and Arthur, 2009). Although estimation of RFI is usually done in young growing cattle, the correlation between RFI in growing cattle and mature cows is significant (Herd et al., 2003). Greater efficiency in low RFI steers compared with high RFI steers may be a result of decreased methane production (Nkrumah et al., 2006; Hegarty et al., 2007) and increased digestibility (Nkrumah et al., 2006). Although RFI may not be a tool for direct estimation of mature cow feed efficiency, selection for low RFI in bulls may indirectly improve efficiency in subsequent generations of mature cows. However, (Bormann et al., 2008) observed that heifers sired by low or high RFI bulls had similar RFI, feed conversion ratio and rate of gain. The relationship between RFI selection in bulls and subsequent efficiency in growing heifers and mature cows is not completely understood. The physiological and molecular basis for efficiency between growing animals with low RFI and mature cows with low MR may be similar. Relationships between variation in MR with heat and methane production, digestive tract efficiency, and animal activity and behavior warrant further investigation.

Summary

Maintenance energy requirements varied 29% between the most and least efficient cows. This supports the concept that selection for greater energetic efficiency is possible in beef cattle. The amount of energy required for maintenance did not influence cow or calf performance, indicating that selection for more efficient cows will likely not negatively impact production output. Improved energetic efficiency has the potential to increase profitability of beef cattle production (Moore et al., 2009). Mechanisms that contribute to variation in energetic efficiency are dynamic and numerous (Herd and Arthur, 2009). Therefore, a combination of physiological tools, such as concentrations of hormones, rumen temperature, heat production, heart rate, and animal behavior, in conjunction with gene expression and proteomics research will likely generate a biomarker for selection of more efficient animals. Identification of cows that require less energy for maintenance, while sustaining performance, will improve efficiency of beef cattle production.

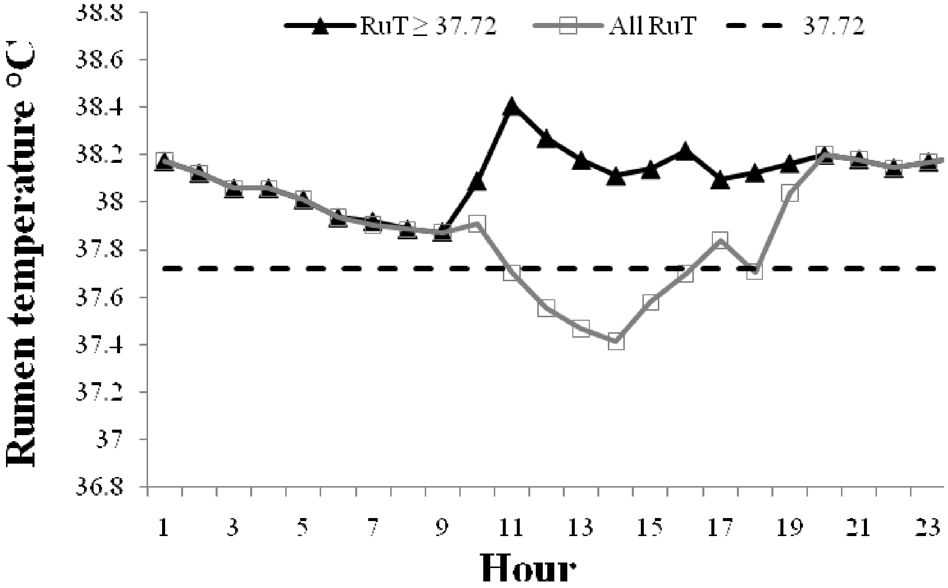

Figure 1. Diurnal variation in mean rumen temperature (RuT) during four consecutive days when cows consumed actual maintenance diets. Grey line includes all RuT values, solid black line excludes RuT values < 37.72°C (dashed line). Cows were fed at 0730 daily and had ad libitum access to water. Hour 1 equals 0100 h.

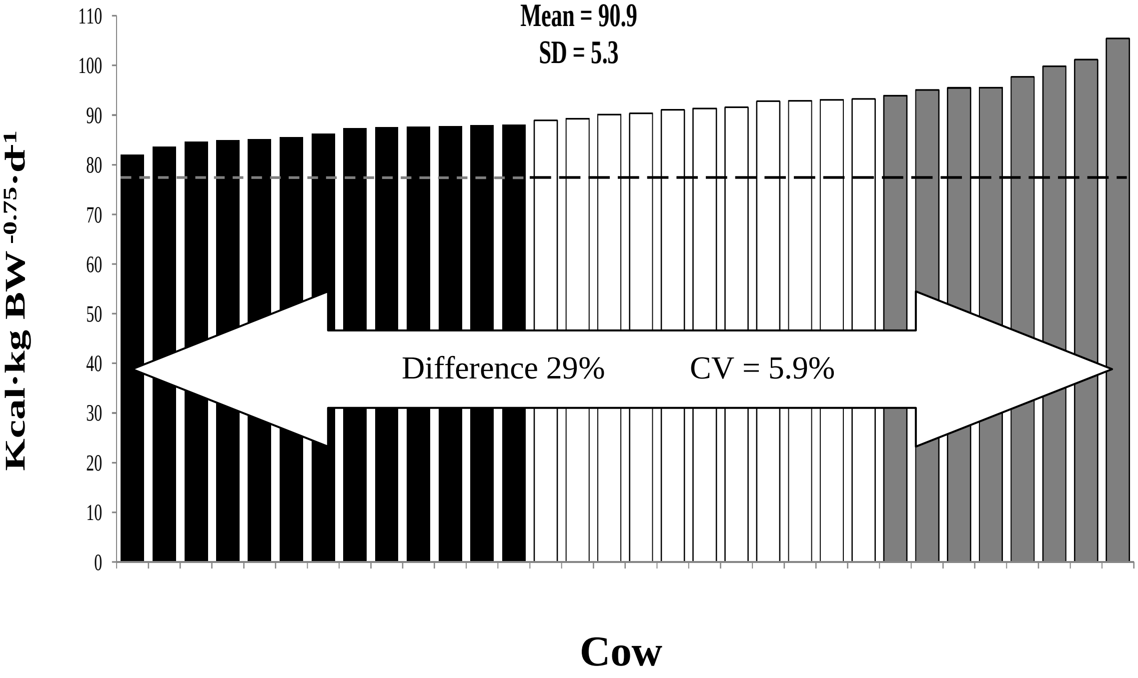

Figure 2. Actual maintenance energy requirements (MR, Kcal·kg BW $^{-0.75}$·d^{-1}) of beef cows during the constant body weight period. Bars represent actual MR of each cow (Black bars = Low MR, white bars = Moderate MR, and grey bars = High MR cows). Cows were classified based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean). Difference equals the percentage MR difference between cows with the greatest and least MR. Mean estimated MR (77.0, NRC 1996, Level 1 Model) is represented by the dashed line.

Table 1. Least squares mean of actual maintenance energy requirements (MR) of beef cows with low (LMR), moderate (MMR) or high (HMR) MR during the constant BW period (at least 17d)[1]

	MR[2]			
Item	LMR	MMR	HMR	SE
Cows, n	13	11	8	
MR	86.03[a]	91.31[b]	98.01[c]	0.81

[1] Maintenance energy requirements (NE_m, Kcal·kg BW $^{-0.75}$·d^{-1}) presented as least squares means per group.

[2] Cows were classified based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean).

[a,b,c] Means within a row without a common superscript differ ($P < 0.0001$)

Table 2. Body weight of beef cows (kg) with low (LMR), moderate (MMR) or high (HMR) maintenance energy requirement (MR)

	MR[1]				
Item	LMR	MMR	HMR	SE	*P* value
Cows, n	13	11	8		
BW Initial[2]	570	583	562	14	0.61
BW Final[3]	572	580	549	14	0.35
BW, 244 d of gestation	623	637	605	16	0.35
Cows, n[4]	12	10	8		
BW 41 d after calving	526	527	513	14	0.76
BW 62 d after calving	537	547	526	14	0.62
BW at Weaning[5]	595	603	597	17	0.92

[1] Cows were classified based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean).

[2] Mean body weight on the first day (Nov 6) of feeding NE_m (NRC).

[3] Mean body weight on the last day (Dec 24) cows were at constant BW.

[4] One cow died shortly after calving and one calf died at birth, excluding 2 cows from the experiment.

[5] 210 ± 6 d after calving.

Table 3. Body condition score of beef cows with low (LMR), moderate (MMR) or high (HMR) maintenance energy requirement (MR)

	MR[1]				
Item	LMR	MMR	HMR	SE	*P* value
Cows, n	13	11	8		
BCS Initial[2]	4.8	5.0	4.8	0.1	0.21
BCS Final[3]	5.0	5.1	4.9	0.1	0.16
BCS, 244 d of gestation	4.9[a]	5.0[a]	4.7[b]	0.1	0.09
Cows, n[4]	12	10	8		
BCS 41 d after calving	4.3[b]	4.5[a]	4.1[b]	0.1	0.08
BCS 62 d after calving	4.5	4.7	4.3	0.1	0.17
BCS 146 d after calving	4.3	4.5	4.3	0.1	0.35
BCS at weaning[5]	4.6	4.7	4.6	0.1	0.74

[1] Cows were classified based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean).

[2] BCS on the first day (Nov 6) of feeding NE_m (NRC).

[3] BCS on the last day (Dec 24) cows were at constant BW.

[4] One cow died shortly after calving and one calf died at birth, excluding 2 cows from the experiment.

[5] 210 ± 6 d after calving.

[a, b, c] Means within a row without a common superscript differ ($P < 0.05$)

Table 4. Body weights of calves (kg) born to dams with low (LMR), moderate (MMR) or high (HMR) maintenance energy requirements (MR)

	MR[1]				
Item	LMR	MMR	HMR	SE	*P* value
Calves, n	13	11	8		
Birth Weight	39	38	39	2	0.89
Calves, n[2]	12	10	8		
BW 62 d of age	96	103	102	4	0.33
BW 146 d of age	183	192	194	7	0.45
Adjusted 205 d weaning weight	196	202	206	8	0.58
ADG[3]	0.96	0.99	1.00	0.04	0.58
Age at weaning	209	211	210	2	0.75

[1] Calves are classified based on MR of their dam, as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean).

[2] One cow died shortly after calving (calf sold) and one calf died at birth, excluding 2 calves from the experiment.

[3] ADG from birth to weaning.

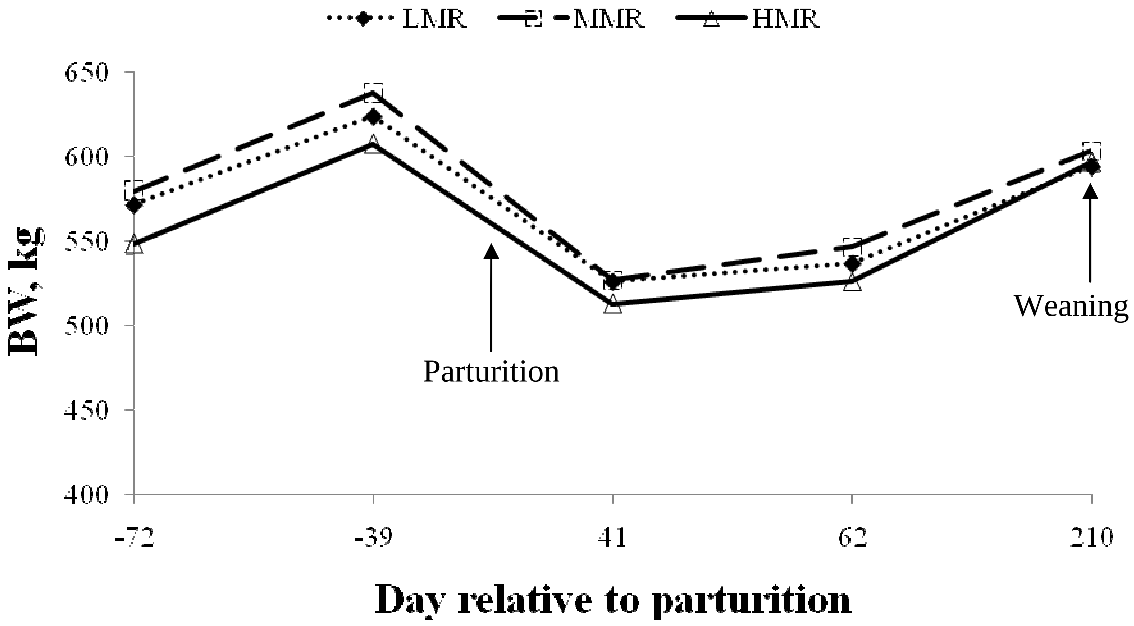

Figure 3. Body weight (BW) of beef cows (kg) with low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean) maintenance energy requirements (MR). Average SE across days was 15 kg.

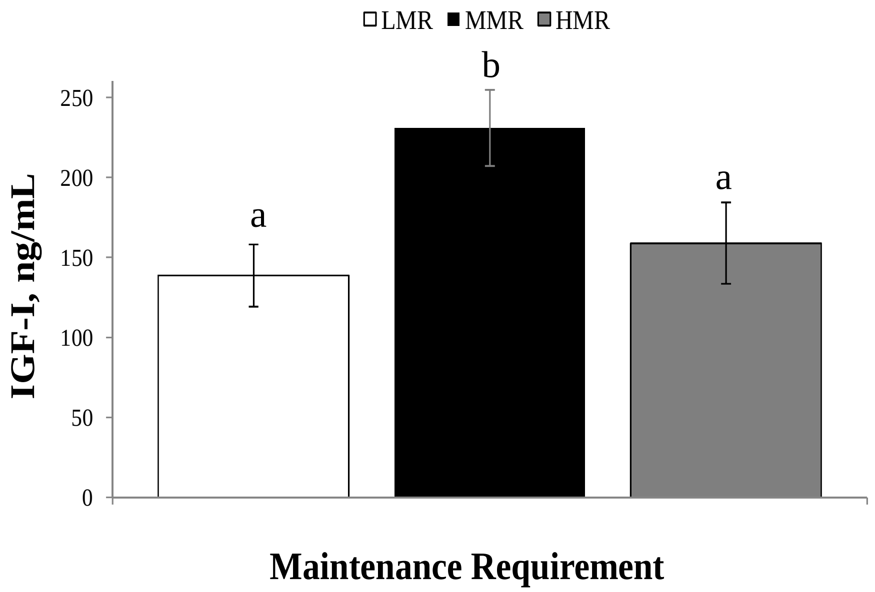

Figure 4. Least squares mean concentrations of IGF-I during the period when cows consumed actual maintenance energy requirement (MR) diets. Cows were classified based on MR as low (LMR; > 0.5 SD less than mean; n = 13), moderate (MMR; ± 0.5 SD of mean; n = 11) or high (HMR; > 0.5 SD greater than mean; n = 8). ^{a,b} Means without a common superscript differ ($P < 0.05$).

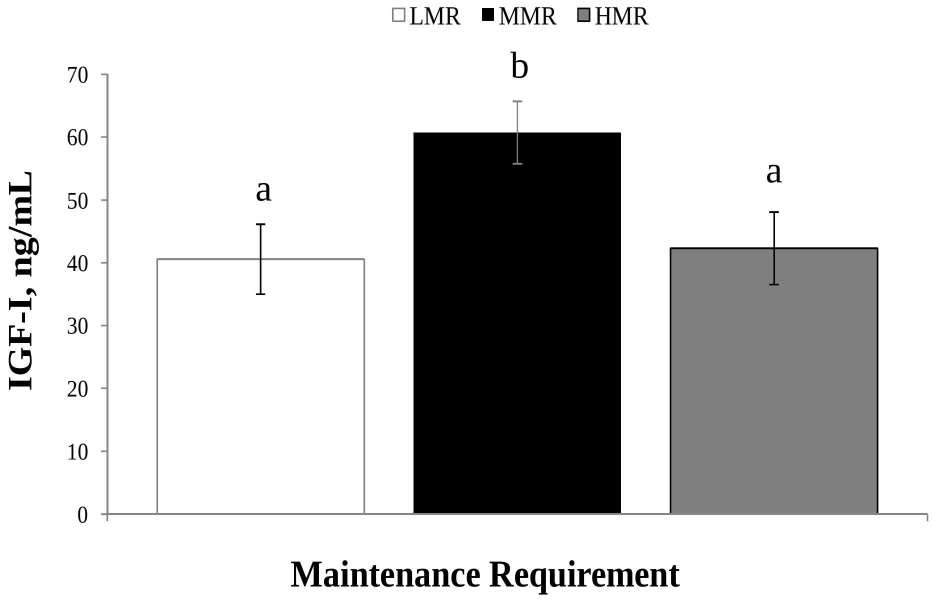

Figure 5. Least squares mean concentrations of IGF-I during early lactation (62 ± 6 d) for cows with Low (n = 13), Moderate (n = 11), and High (n = 8) maintenance energy requirements (MR). Cows were classified based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean). ^{a,b} Means without a common superscript differ ($P < 0.05$).

Table 5. Effects of sample on concentrations of IGF-I, glucose, insulin, and thyroxine in plasma of beef cows fed to maintain body weight or grazing native range[1]

	Day 1		Day 2				
	Sample[2]					P value	
Item	1	2	1	2	SE	Sample	MR x Sample
MR Period (n = 32)							
IGF-I, ng/mL	179.9	165.0	181.7	176.2	20.0	0.50	0.57
Glucose, mg/dL	71.6^{a}	68.6^{b}	71.4^{a}	70.4^{ab}	1.1	0.08	0.25
Insulin, ng/mL	0.29	0.27	0.30	0.29	0.02	0.57	0.14
Thyroxine, ng/mL	51.0	51.2	52.4	52.0	1.8	0.66	0.34
Early Lactation (n = 30)							
IGF-I, ng/mL	52.5^{a}	41.5^{b}	49.3^{a}	48.2^{a}	5.5	< 0.003	0.82
Insulin, ng/mL	0.29^{a}	0.22^{b}	0.29^{a}	0.26^{ab}	0.01	< 0.001	0.86
Thyroxine, ng/mL	33.8^{a}	34.5^{a}	34.7^{a}	39.9^{b}	0.9	< 0.001	0.12

[1] Blood was sampled twice daily on consecutive days from non lactating, pregnant cows during the period when cows consumed actual maintenance energy requirement (MR) diets (MR Period) and from non-pregnant cows grazing native range 62 ± 6 d after calving (Early Lactation). [2] Samples were taken at 0700 and 1500 each day. [a,b,c] Means within a row without a common superscript differ ($P < 0.05$)

Table 6. Concentrations of IGF-I, glucose, insulin, and thyroxine in plasma of beef cows with low (LMR), moderate (MMR) or high (HMR) maintenance energy requirements (MR)

	MR[1]				
Item	LMR	MMR	HMR	SE	*P* value
MR Period[2]					
Cows, n	13	11	8		
IGF-I, ng/mL	138.7[a]	231.0[b]	158.9[a]	22.9	0.03
Glucose, mg/dL	69.7	71.3	70.4	1.6	0.69
Insulin, ng/mL	0.27	0.29	0.24	0.02	0.22
Thyroxine, ng/mL	50.7	51.7	52.7	2.7	0.86
Early Lactation[3]					
Cows, n[4]	12	10	8		
IGF-I, ng/mL	40.6[a]	60.7[b]	42.3[a]	5.9	0.03
Insulin, ng/mL	0.31	0.29	0.26	0.01	0.13
Thyroxine, ng/mL	35.5	37.6	34.1	1.2	0.21

[1] Cows were classified in groups based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean).

[2] Samples were obtained during the period when cows consumed actual MR diets.

[3] Samples were obtained 62 d after calving from cows grazing native range.

[4] Two cows were removed from the experiment after calving.

[a,b,c] Means within a row without a common superscript differ ($P < 0.05$).

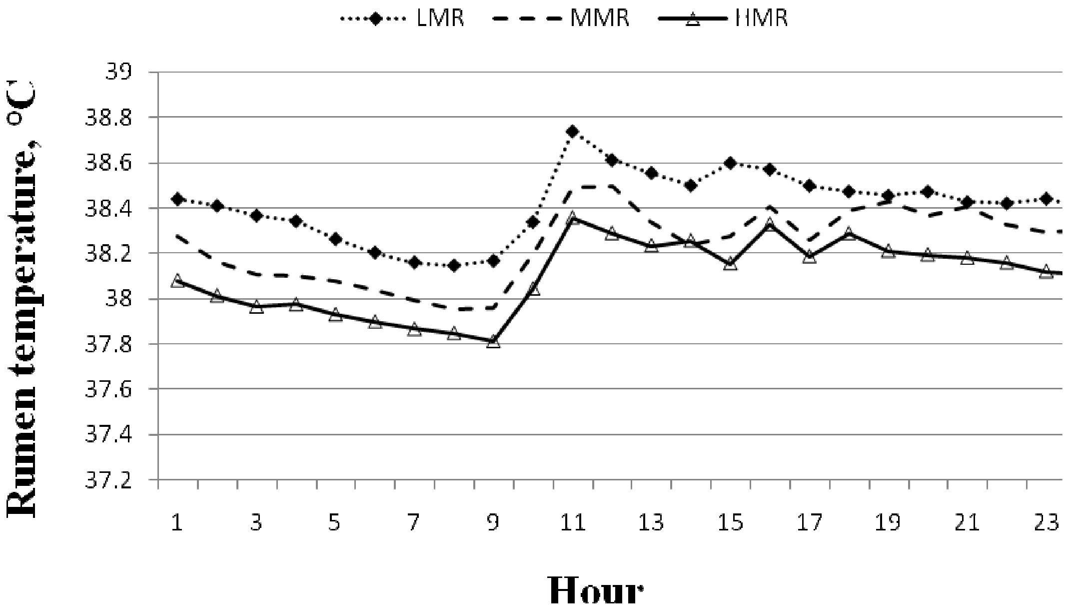

Figure 6. Diurnal variation in mean rumen temperature (RuT) for cows with low, moderate or high maintenance energy requirements (MR) during four consecutive days when cows consumed actual maintenance diets. Cows were classified based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean) MR. There was an hour effect (*P* < 0.0001) but no MR x hour effect (*P* = 0.99) on mean RuT. Cows were fed at 0730 daily and had ad libitum access to water. Hour 1 equals 0100 h. RuT values < 37.72°C were excluded.

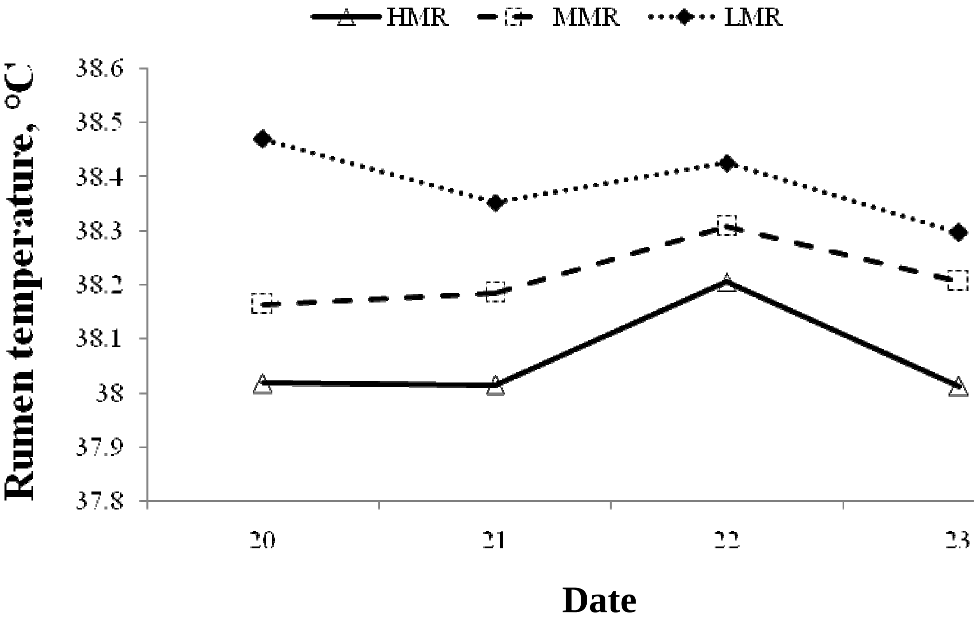

Figure 7. Maintenance energy requirement (MR) x date interaction for rumen temperature (RuT) including 24 h per day during four consecutive days when cows consumed actual maintenance diets (December 20 to 23). Cows were classified in groups based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean). MR x date (*P* = 0.04). Average SE across days was 0.1.

Table 7. Rumen temperature (RuT) of beef cows with low (LMR), moderate (MMR) or high (HMR) maintenance energy requirements[1]

	MR Group[2]				
Item	LMR	MMR	HMR	SE	*P* value
Maintenance					
RuT 24 hr per day[4]	38.39^{a} (12)[3]	38.22^{ab} (11)	38.06^{b} (8)	0.08	0.05
RuT 20 hr per day[5]	38.36 ^{a} (12)	38.19 ^{ab} (11)	38.06 ^{b} (8)	0.09	0.09
Early Lactation					
RuT 24 hr per day[4]	38.60 (4)	38.55 (6)	38.29 (4)	0.14	0.40
RuT 20 hr per day[5]	38.34 (4)	38.42 (6)	38.04 (4)	0.17	0.31

[1] Mean rumen temperatures (°C) per cow during four consecutive days when cows consumed actual MR diets (Maintenance) and t consecutive days, 68 d after calving (Early Lactation).

[2] Cows were classified in groups based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean).

[3] Number of cows in parentheses.

[4] RuT for all 24 each day were included in analyses.

[5] RuT between 0900 and 1200 were excluded from analyses.

[a,b] Means within a row without a common superscript differ ($P < 0.05$)

Table 8. Effect of day on rumen temperature (RuT) of beef cows fed to maintain body weight (BW)[1]*

	Day					
Item	1	2	3	4	SEM	*P* value
RuT 24 hr per day[2]	38.22^{a}	38.18^{a}	38.31^{b}	38.17^{a}	0.06	< 0.001
RuT 20 hr per day[3]	38.20^{ab}	38.19^{ab}	38.28^{b}	38.15^{a}	0.06	< 0.006

[1] Mean rumen temperatures per cow during four consecutive days when cows consumed actual MR diets were (Maintenance).

[2] RuT for all 24 each day were included in analyses.

[3] RuT between 0900 and 1200 were excluded from analyses.

[a,b] Means within a row without a common superscript differ ($P < 0.05$)

* Mean daily ambient temperature did not influence rumen temperature ($P \geq 0.41$)

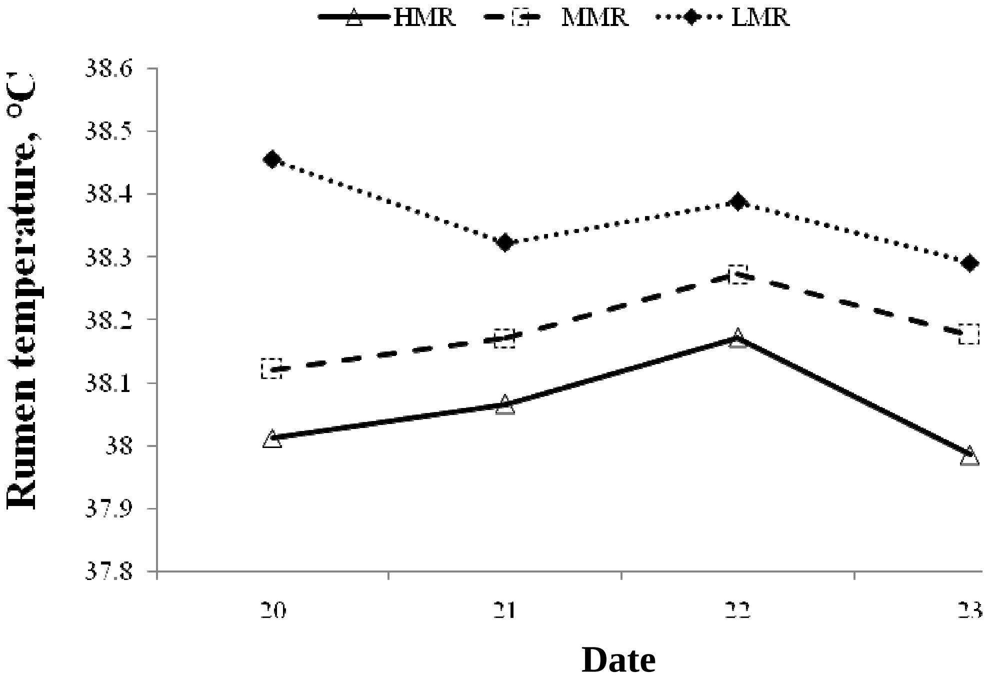

Figure 8. Maintenance energy requirement (MR) x date interaction for rumen temperature (RuT) including 20 h per day during four consecutive days when cows consumed actual maintenance diets (December 20 to 23. RuT between 0900 and 1200 were excluded from analyses. Cows were classified in groups based on MR as low (LMR; > 0.5 SD less than mean), moderate (MMR; ± 0.5 SD of mean) or high (HMR; > 0.5 SD greater than mean). MR x day (P = 0.05). Average SE across days was 0.1.

CHAPTER IV

ESTRUS DETECTION IN BEEF COWS WITH RUMEN TEMPERATURE

ABSTRACT: Angus cows, 4 to 8 yr of age, were used to evaluate changes in rumen temperature (RuT) associated with estrus. Temperature boluses (SmartStock, LLC) were placed in the rumen with a balling gun during gestation. Boluses were programmed to transmit RT hourly. Estrus of cows (BW = 539 ± 44 kg, BCS = 4.5 ± 0.4) was synchronized with $PGF_{2\alpha}$ at 79 ± 14 d after calving in May (n = 25) or 85 ± 22 d after calving in December (Dec, n = 30). The HeatWatch® Estrus Detection System (CowChips, LLC) was used to monitor onset of estrus. Rumen temperatures recorded 96 h before to 72 h after estrus were analyzed. Mean RuT during the first 8 h after onset of estrus in May (39.2 ± 0.1°C, n = 17) was greater ($P < 0.001$) than RuT during 16 to 32 h before estrus (38.2 ± 0.1°C, n = 15) or 16 to 32 h after estrus (38.0 ± 0.1°C, n = 19). Similarly, mean RuT during the first 8 h after onset of estrus in Dec (38.8 ± 0.1°C, n = 18) was greater ($P < 0.001$) compared with RuT 16 to 32 h before estrus (38.3 ± 0.1°C, n = 21) or 16 to 32 h after estrus (38.2 ± 0.1°C, n = 19). Increases in mean RuT for any 8 h period ≥ 0.3°C, ≥ 0.5°C or ≥ 0.7°C above the mean for a cow during 12 to 84 h preceding the 8 h increase were used as criteria to predict estrus. An increase in RuT ≥ 0.3°C or ≥ 0.7°C correctly predicted estrus in 100% and 70% of estrous cows, respectively, in Dec;

100% of estrous cows in May were correctly predicted using either criterion. An increase in RuT ≥ 0.3°C identified non-estrus cows as estrus in 72% of cows in May and 55% of cows in Dec. An increase in RuT ≥ 0.7°C identified one non-estrus cow (1/25) as estrus in May. Rumen temperature did not increase ≥ 0.7°C when cows were non-estrus in Dec (0/29). Daily mean ambient temperatures during collection of RuT at estrus (Oklahoma Mesonet) were 24.0 ± 2.9°C in May and 2.7 ± 4.5°C in Dec. Mean ambient temperature ranged from 18°C to 29°C in May and -3°C to 8°C in December. Mean RuT increased in cows at estrus in both May and Dec breeding seasons. The use of RuT has potential application for detection of estrus in beef cows.

INTRODUCTION

The use of AI has the potential to increase revenue in beef operations by improving the genetic potential of the cow herd. However, less than 10% of beef operations in the U.S. use AI, citing time and labor associated with estrous detection as primary limiting factors (USDA, 2009). Estrous synchronization enhances the use of AI, increases the genetic potential to produce meat and milk, and can increase efficiency of beef and dairy production (Lauderdale, 2009). Frequent visual observation, with or without the use of estrous detection aids, is effective but often cost prohibitive and impractical in many beef operations. Successful estrous detection by visual observation requires considerable time and dedication by producers (At-Taras and Spahr, 2001).

Several remote sensing systems have been developed that continuously detect estrus by evaluating body temperature without the need for handling or visual observation. Vaginal temperatures increase from 0.6 to 0.9°C for approximately 7 h during estrus (Redden et al., 1993; Kyle et al., 1998). Positive relationships between body temperature increases and the LH surge have been indicated (Rajamahendran et al., 1989; Clapper et al., 1990; Mosher et al., 1990; Fisher et al., 2008). Although systems to monitor vaginal and body temperature have potential, practical systems to predict estrus are not currently commercially available (Rorie et al., 2002).

Rumen boluses (SmartStock, LLC) have been developed to record rumen temperature (Dye, 2007). Using radiotelemetry to send data to a computer, rumen boluses allow frequent body temperature evaluation with minimal impact on animal behavior and may be a useful method to detect estrus. To be widely accepted, systems that evaluate body temperature must minimize labor, have acceptable longevity, have minimal impact on animal behavior, and provide frequent, accurate temperature data. Successful estrus detection systems must be accurate and effective, economical, user friendly, and directly contribute to profitability (Senger, 1994). The use of rumen temperature boluses to quantify body temperature and predict estrus warrants further investigation. Therefore, objectives of this study were: (1) to evaluate rumen temperature at estrus in beef cows during May and December breeding seasons, (2) to develop a method to predict estrus with rumen temperature, (3) and to evaluate seasonal influences on rumen temperature at estrus.

MATERIALS AND METHODS

Animals and management

Experimental procedures used in this study were approved by the Oklahoma State University Animal Care and Use Committee. Spring calving (n = 25) or fall calving (n =

30) Angus cows, 4 to 8 yr of age, were used to evaluate changes in rumen temperature (RuT) associated with estrus. Estrus of cows (BW = 539 ± 44 kg, BCS = 4.5 ± 0.4) was synchronized with $PGF_{2\alpha}$ (Lutalyse® 25 mg, i.m.; Pharmacia & Upjohn Co., Pfizer, Inc., New York, NY) at 79 ± 14 d after calving in spring cows or 85 ± 22 d after calving in fall cows. Cows that did not respond to the initial $PGF_{2\alpha}$ injection were administered a second treatment 10 d after the first treatment.

Onset of estrus was monitored with the HeatWatch® Estrus Detection System (CowChips, LLC, Manalapan, NJ) and was defined as the first two mounts within a 4 h period. The end of standing estrus was defined as the last mount received within 4 h of another mount, with no mounts occurring during the next 12 h (White et al., 2002). Nylon patches containing pressure sensors with radio transmitters were attached to the tailhead with adhesive at the time of the initial $PGF_{2\alpha}$ treatment. Proper placement and attachment of patches were observed daily and were maintained as necessary. Cows were AI to Angus bulls 13 ± 2 hours after onset of estrus in either May or December.

Rumen Temperature Measurement

Rumen temperature boluses (8.25 cm x 3.17 cm; 114 g) with individual identification numbers were placed into the rumen-reticulum of each cow with a custom balling gun. A data recovery system (SmartStock®, LLC, Pawnee, OK) was installed at the South Range Cow Research Center to record RuT. Three antennas installed on the perimeter fence of the pasture (3.2 ha), where cows were maintained, recorded and transmitted data hourly from each bolus. Each RuT recording also included temperatures for each of the previous 12 h. Data were relayed 100 m from collection antennas to a receiver antenna at the office. Rumen temperature, time, date and cow identification were transmitted hourly to a computer equipped with software compatible with the RuT collection system. Rumen temperatures were recorded from 96 h before to 72 h after estrus from May 16 to June 5 (May) and from Dec 1 to Dec 19 (Dec).

Statistical analyses

Exclusion of RuT outliers reduced variation associated with water consumption (Dye, 2007; Prado, 2009). Outliers associated with water consumption were identified using the UNIVARIATE procedure of SAS (SAS Institute Inc., Cary, NC) to evaluate the distribution and degree of skewness of data. Deletion of values < 35.3°C in May and < 36.3°C in Dec omitted 4.3% and 1.2% of RuT values, respectively, and reduced skewness and variance of RuT data.

Mean RuT for several different periods relative to onset of estrus (HeatWatch®) were compared (Figure 9): RuT from 8 h before to 8 h after onset of estrus (0 h) was compared with the same daily hours the day before (-32 to -16 h) and the day after (16 to 32 h), RuT from 4 h before to 4 h after onset of estrus compared with the same daily hours the day before (-28 to -20 h) and the day after (20 to 28 h), and RuT from onset of estrus to 8 h after onset of estrus was compared with the same daily hours the day before (-24 to -16 h) and the day after (24 to 32 h). Periods were selected based on information about estrous behavior, vaginal and body temperature at estrus, and preliminary data for RuT at estrus (Prado, 2009). Mean RuT were compared between time periods on the day of estrus and similar daily hours the day before and after estrus because RuT had diurnal variation in previous research (Prado, 2009) and in this study (Figures 10 and 11).

Rumen temperature data were analyzed using the MIXED procedure of SAS with day as a repeated measurement within cow and period as a fixed effect. Models included daily mean ambient temperature (Oklahoma Mesonet, Marena Station) as a covariable. Cows with less than three RuT values in a period were excluded from the analysis. To be considered for evaluation ≥ 3 RuT values per period were required. Six covariance structures (variance component, compound symmetry, Huynh-Feldt, first-order autoregressive, Toepliz, and unstructured) were evaluated to identify the best structure according to the goodness of fit statistics. Variance components for analyses were estimated using the restricted maximum-likelihood method. Denominator degrees of freedom were determined using the Kenward-Roger procedure. The covariance structures with the best goodness of fit were variance component and Toplitz for RuT in May and Dec, respectively. When effects were significant least squares means were compared using LSD (pdiff option of SAS).

Criteria for detection of estrus were developed based on changes in RuT at the onset of estrus. Cows were identified as estrus when an 8 h mean RuT was 0.3°C, 0.5°C, or 0.7°C greater than a pre-estrus average RuT (determined for each cow). The pre-estrus average RuT was calculated for a 72 h period that ended 12 h preceding the start of the 8 h increase used to identify estrus (Figure 12). The pre-estrus mean RuT included ≥ 24 RuT values and mean 8 h estrus identification periods included ≥ 4 RuT values. When ≥ 5 RuT values were not recorded during 8 h before to 8 h after estrus, the cow was excluded from estrous detection analyses but was evaluated for increases in RuT when cows were not estrus. Adequate RuT values, both at estrus and during pre-estrus, were recorded in 35% (10/29) of cows in December and 68% (17/25) of cows in May. Each cow was evaluated for increases in RuT when a cow was non-estrous and failure to increase RuT when a cow was estrus. One bolus failed to record RuT, omitting one cow in Dec.

RESULTS

Daily mean ambient temperatures (Oklahoma Mesonet) during evaluation of RuT at estrus was 24.0 ± 2.9°C in May and 2.7 ± 4.5°C in Dec, and ranged from 17°C to 29°C in May and -4°C to 14°C in Dec. When daily mean ambient temperature was included as a covariable, it did not influence RuT in May ($P = 0.35$) but did influence RuT in Dec ($P < 0.001$). Mean rumen temperature of cows from 96 h before to 72 h after onset of estrus was 38.2 ± 0.3°C and 38.3 ± 0.4°C in May and Dec, respectively.

Rumen temperatures relative to the onset of estrus, with and without excluding values associated with water consumption, are presented in Figure 13 (May) and Figure 14 (Dec). Mean RuT was greater from 8 h before to 8 h after onset of estrus compared with similar daily hours the day before and day after estrus (Table 9) in both May ($P < 0.001$) and Dec ($P < 0.001$). Similarly, mean RuT was greater from 4 h before to 4 h after onset of estrus compared with similar daily hours the day before and after estrus in both Dec ($P < 0.001$) and May ($\mathrm{P} < 0.004$). Mean RuT was also greater in both May ($P < 0.001$) and Dec ($P < 0.001$) during the first 8 h after onset of estrus compared with the same 8 daily hours the day before and after onset of estrus. In May, mean RuT during the first 8 h of estrus was 1.05°C and 1.2°C greater than the same daily hours the day before and the day after estrus, respectively (Figure 15). During the first 8 h of estrus in Dec, mean RuT was 0.59°C greater than the same 8 h the day before and 0.68°C greater than the same 8 h the day after estrus (Figure 16).

Increases in 8 h mean RuT of 0.3°C, 0.5°C or 0.7°C greater than the pre-estrus average identified 100%, 80%, and 70% of estrous cows in Dec, and 100% of estrous cows were identified in May using any of the three criteria (Table 10). When cows were non estrus, 8 h mean RuT increased ≥ 0.3°C or ≥ 0.5°C above the pre-estrus mean in 55% and 10% of cows in Dec and 72% and 16% of cows in May. One non estrus cow in May had a RuT increase ≥ 0.7°C above the pre-estrus mean. None of the non-estrus cows in Dec had RuT increases ≥ 0.7°C. Mean RuT did not increase ≥ 0.5°C or ≥ 0.7°C when cows were estrus in 20% and 30% of cows in Dec, respectively; RuT increased ≥ 0.7°C compared with pre-estrus average in all estrus cows in May. Increases in 8 h mean RuT 0.3°C, 0.5°C or 0.7°C greater than the pre-estrus average first identified estrus of cows 0.8 ± 4.5 h, 2.5 ± 4.5 h, and 3.6 ± 4.5 h, respectively, after the onset of estrus (HeatWatch®) in May and 3.2 ± 5.5 h, 4.5 ± 3.4, and 6.9 ± 2.0 h, respectively, after onset of estrus in Dec.

DISCUSSION

Onset of estrus was monitored with the HeatWatch® Estrus Detection System. When cows were visually observed for 28 h, the number of mounts received per cow determined by HeatWatch was correlated with the number of mounts detected visually ($r = 0.91$; $P < 0.001$), and every estrus detected visually was also detected by HeatWatch (Floyd et al., 2009). HeatWatch® is 78 to 100% accurate and 90 to 100% efficient in detecting estrus (Stevenson et al., 1996; Timms et al., 1997; Xu et al., 1998).

Mean RuT of cows from 96 h before to 72 h after onset of estrus was similar during the May and Dec breeding seasons. Daily mean ambient temperature influenced

RuT in Dec but not in May. The relationship between ambient temperature and body temperature when cattle are in the thermal-neutral zone is not established. Ambient temperature did not influence changes in RuT (Prado, 2009), vaginal temperature (Kyle et al., 1998), or rectal temperature (Piccione et al., 2003). Frequency of ambient temperature measurement and method of analysis (mean, max, min, etc.) may influence ambient temperature effects on body temperature. Ambient temperatures have minimal effect on body temperature unless cows are exposed to very hot or cold temperatures (Zartman and Dealba, 1982).

Greater variation in ambient temperature was recorded in Dec compared with May. The average difference between daily maximum and minimum ambient temperature was 11.1 ± 2.8°C in May and 10.4 ± 6.9°C in Dec. Ambient temperature ranged (actual coldest to warmest) from 10°C to 33°C in May and from -9°C to 19°C in Dec. In Oklahoma, ambient temperature can change dramatically in a very short period of time. Ambient temperature on individual days in Dec varied from -3°C to 19°C (Dec 2) and from -5°C to 17°C (Dec 19). In December, it is not uncommon for ambient temperature to fluctuate by 20 to 25°C in a 24 h period, while ambient temperature is typically less variable in May. Extreme temperature changes in December may have contributed to ambient temperature effects on RuT in Dec. Mean daily ambient temperature may not be precise or frequent enough to effectively evaluate the influence of ambient temperature on RuT. Other variables such as rainfall, humidity, wind speed and animal factors may need to be incorporated to better evaluate environmental effects on RuT.

The magnitude and duration of the decline in rumen temperature due to water consumption depends on the volume and temperature of water consumed (Brod et al., 1982; Dye, 2007; Bewley et al., 2008). Excluding outlier values associated with water consumption (< 35.3°C, May and < 36.3°C, Dec) reduced skewness and variance and improved the distribution of RuT data. When outliers, associated with water consumption, were included in analyses, RuT at estrus increased compared with same daily hours the day before and the day after estrus (Table 11). Rumen temperatures during the hours before and after estrus were comparable between models with or without outliers. When outliers were included, mean RuT the day before and day after estrus were about 0.5°C less compared with period analyses excluding outliers. Consumption of water decreases during estrus (Lukas et al., 2008). Normal water consumption during the days before and after estrus, and reduced water consumption during estrus, may explain decreased RuT the day before and after estrus when outliers are included compared with deleting outliers, and similar temperatures at estrus with or without inclusion of outliers. It may be especially important to exclude outliers when using RuT to detect estrus as water consumption during standing estrus could disguise RuT increases, diminishing the accuracy of identifying estrous cows.

Mean RuT increased from 8 h before to 8 h after estrus, 4 h before to 4 h after estrus, and during the first 8 h after onset of estrus compared with similar daily hours the day before and the day after estrus. During the first 8 h of estrus, mean RuT was 1.05°C and 0.59°C greater than the same daily hours the day before estrus in May and Dec, respectively. The increase in RuT at estrus in this study is in agreement with increases in body temperature (Clapper et al., 1990; Mosher et al., 1990), vaginal temperature

(Redden et al., 1993; Kyle et al., 1998; Fisher et al., 2008) and RuT (Prado, 2009; Wright, 2009) at estrus. Mean RuT was 0.61°C greater during the first 8 h after estrus was first detected with twice daily observation compared with similar hours the day before and day after estrus (Prado, 2009). Vaginal temperatures increased from 0.6 to 0.9°C for approximately 7 h during estrus (Redden et al., 1993; Kyle et al., 1998) and Fisher et al. (2008) observed vaginal temperature increased 0.48°C at estrus. Multiparous Holstein cows ovulated 22 ± 3 h after maximum vaginal temperature (Rajamahendran et al., 1989). Rectal temperature of cows increased 1.3°C on the day of estrus, with minimal seasonal variation (Piccione et al., 2003).

Many factors such as physical activity, water consumption, feed intake and endocrine secretions may influence body temperature at estrus. Cows increased physical activity (Kiddy, 1977; Pennington et al., 1986) and decreased water consumption (Lukas et al., 2008) at estrus. Mean tympanic temperature increased from 0.3 to 0.8°C after moving feedlot cattle 600 m (Mader et al., 2005). Feed intake and water consumption likely contribute to variation in rumen temperature and require further investigation. Endocrine changes at estrus may impact body temperature of cows (Wrenn et al., 1958). Uterine blood flow increased in ovariectomized dairy cows when treated with estradiol-17β (Roman-Ponce et al., 1983). Increases in uterine blood flow during 4 d before to 1 d after estrus were positively associated with estradiol and estrone to progesterone concentrations and negatively associated with concentrations of progesterone in plasma of sheep (Roman-Ponce et al., 1978). Changes in plasma concentrations of estradiol and blood flow at estrus may influence RuT at estrus. Plasma concentrations of estradiol are associated with the ovulatory surge of LH in beef cows (Wettemann et al., 1972) and are greatest on the day of estrus (Stevensen et al., 1998; White et al., 2002). A positive relationship has been established between body temperature increases relative to the time of the surge of LH (Rajamahendran et al., 1989; Clapper et al., 1990; Mosher et al., 1990; Fisher et al., 2008).

The increase in mean RuT during the first 8 h of estrus was more pronounced in May (1.05°C) than in Dec (0.59°C). Cows exposed to warmer ambient temperatures may have more difficulty dissipating body heat associated with estrus compared with cows in cooler environments. Factors that influence estrous behavior may influence the degree of RuT changes at estrus. Season and ambient temperature appear to influence estrus behavior; however, the extent of this interaction is not well established. The duration and severity of temperature stress, cattle genetics, management practices and animal insulation factors likely influence estrous behavior during temperature stress.

Trimberger (1948) concluded that season did not influence estrous behavior of dairy cows monitored twice daily for estrus. Similarly, increased ambient temperature did not influence the duration of estrus in dairy cows monitored with HeatWatch® (Walker et al., 1996). Beef cows were in estrus longer in summer compared with spring and received more mounts with a greater interval between mounts in winter than spring or summer; however, time of ovulation relative to onset of estrus was not influenced by season (White et al., 2002). Dairy cows were in estrus longer with increased interval between mounts in hot weather, and cows received more mounts in cold weather (Pennington et al., 1985). The influence of season on estrous behavior and its impact on body temperature changes at estrus are complex and often confounded with multiple factors that influence estrous behavior. Willingness of herd mates to mount, rather than physiological effects of temperature on estrus cows may help explain seasonal effects on estrous behavior (White et al., 2002). Further investigation of the roles of feed and water consumption and animal behavior on RuT should be pursued.

Increases in 8 h mean RuT of 0.3°C, 0.5°C or 0.7°C greater than the pre-estrus average identified 100% , 80%, and 70% of estrous cows in Dec, and 100% of estrous cows were identified in May using any of the three criteria. There may be seasonal differences in the RuT change at estrus. Identification of estrous cows was more accurate in May because cows had greater RuT increases during estrus compared with cows in Dec. An increase in vaginal temperature ≥ 0.3°C above the mean for the previous 3 d or 4 d correctly predicted estrus in 78% of 9 cows (Mosher et al., 1990) and 81% of 21 cows (Redden et al., 1993). Fisher et al. (2008) developed an algorithm that identified the time of the LH surge relative to maximal vaginal temperature and predicted time of ovulation. Studies were conducted in spring (Fisher et al., 2008; daily ambient temperature ranged from 6 to 19°C), and from August to Dec (Redden et al., 1993; barn temperature ranged from 2 to 26°C). Mosher et al (1990) maintained heifers in individual stalls within a temperature controlled building.

Increases in 8 h mean RuT ≥ 0.3°C or ≥ 0.5°C when cows were non estrous were recorded in 55% and 10% of cows in Dec and 72% and 16% of cows in May. One non estrous cow out of 29 evaluated in May had RuT increases ≥ 0.7°C above the pre-estrus average. None of the non estrous cows in Dec had RuT increases ≥ 0.7°C. Using increases in RuT ≥ 0.3°C for identification of estrus cows was inaccurate in both breeding seasons because too many non estrous cows were identified as estrus. Mean RuT did not increase ≥ 0.5°C or ≥ 0.7°C when cows were estrus in 20% and 30% of cows in Dec, respectively; RuT increased above the pre-estrus average in all estrous cows in May. All cows in May had increases in RuT ≥ 1.0°C at estrus, thus a greater temperature increase can be used to successfully identify estrous cows while minimizing the number of cows not detected and the number of non estrus cows identified as estrus. Increases in 8 h mean RuT above 0.7°C identified all estrous cows in May and 70% of estrous cows in Dec, and only identified one non estrus cow as estrus in either season (54 cows). Cows exposed to colder environments may require different criteria for detection of estrus than cows in warmer environments. Rumen temperature of estrous cows in Dec did not increase as dramatically as RuT of estrous cows in May. Criteria for detection of estrous in Dec may need to be slightly altered compared with those in May to maximize accuracy of identifying cows in estrus.

Differences in the frequency and completeness of RuT values recorded may have contributed to difference in estrous detection results between May and Dec. Adequate RuT values, both at estrus and during pre-estrus mean calculation, were recorded in 35% of cows in Dec and 68% of cows in May. Failure to record sufficient RuT values occurred in more cows in Dec compared with May and may have influenced differences in accuracy of estrus identification between seasons.

Increases in 8 h mean RuT of 0.3°C, 0.5°C or 0.7°C greater than the pre-estrus average first identified estrus of cows at 0.8 ± 4.5 h, 2.5 ± 4.5 h, and 3.6 ± 4.5 h, respectively, after the onset of estrus (HeatWatch®) in May and 3.2 ± 5.5 h, 4.5 ± 3.4, and 6.9 ± 2.0 h, respectively, after onset of estrus in Dec. Vaginal temperatures increased by 0.6°C at estrus and remained elevated ≥ 0.3°C for 6.8 ± 4.6 h (Redden et al., 1993). Vaginal temperature increased 21.1 ± 6.1 h before ovulation (Mosher et al., 1990).

Increases in RuT occurred shortly after onset of estrus in this study, providing sufficient warning for suitable timing of AI relative to ovulation.

Summary

Development of a real time RuT system for detection of estrus that is accurate and reliable offers advantages over current estrus detection systems, and has potential for commercial application. Rumen boluses allow frequent evaluation of body temperature with minimal impact on animal behavior. Increases in 8 h mean RuT ≥ 0.7 C compared with pre-estrus average RuT identified all estrous cows in May and 70% of estrous cows in Dec, and only identified one non estrus cow as estrus in either season. Future research should focus to better understand the roles of feed and water consumption, animal behavior, and environmental factors on RuT as well as the extent of the relationship between RuT and core body temperature. This study indicates that effects of season and/or ambient temperature should be further evaluated to develop prediction models for detection of estrus in beef cows. Decreasing labor associated with estrous detection while maintaining a high degree of accuracy will likely increase the use of AI in beef cows and improve the efficiency and profitability of beef operations.

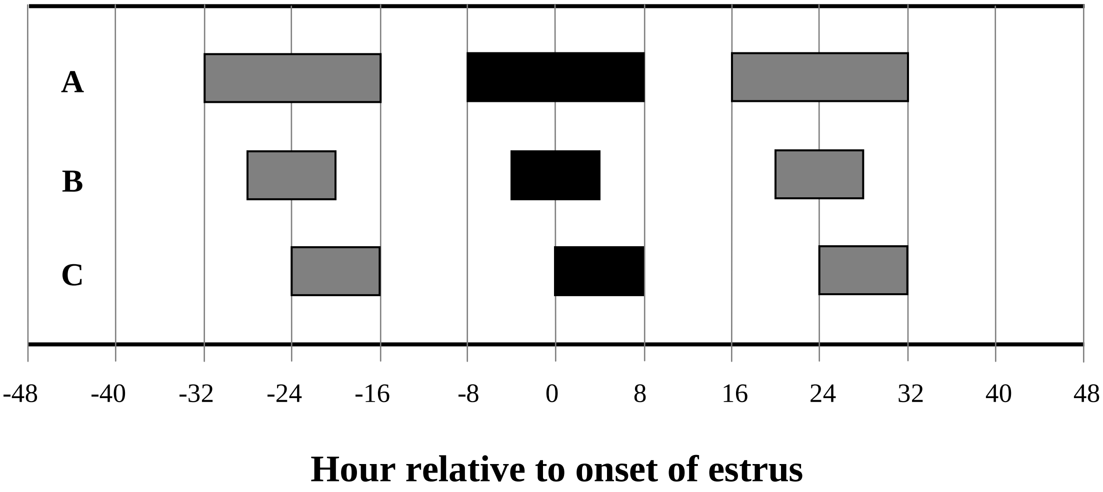

Figure 9. Time periods for comparison of rumen temperatures relative to onset of estrus (h 0) detected by HeatWatch®. **A**: Period from 8 h before to 8 h after onset of estrus was compared with the same daily hours the day before (-32 to -16 h) and the day after 16 to 32 h). **B**: Period from 4 h before to 4 h after onset of estrus was compared with the same daily hours the day before (-28 to -20 h) and the day after (20 to 28 h). **C**: Period from onset of estrus (h 0) to 8 h after onset of estrus was compared with the same daily hours the day before (-24 to -16 h) and the day after (24 to 32 h). Mean rumen temperatures for each cow for these periods were calculated and compared.

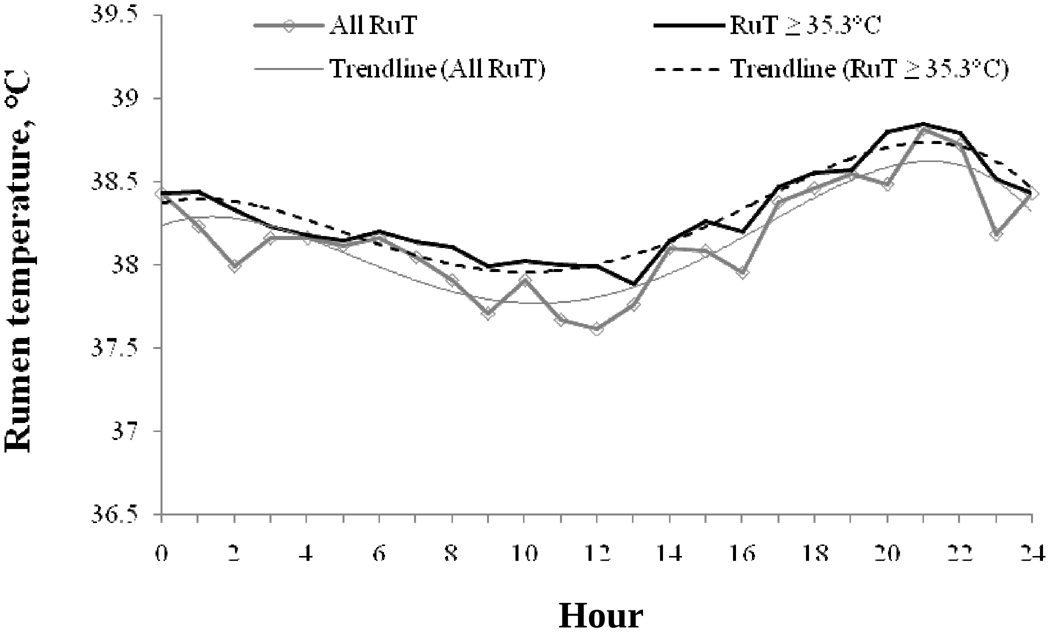

Figure 10. Mean hourly rumen temperature (RuT) of beef cows in May (n = 25) from 72 h before to 72 h after onset of estrus. Gray line is all RuT values, black line excludes values < 35.3°C (water drinking events). Hour 12 equals 1200 h.

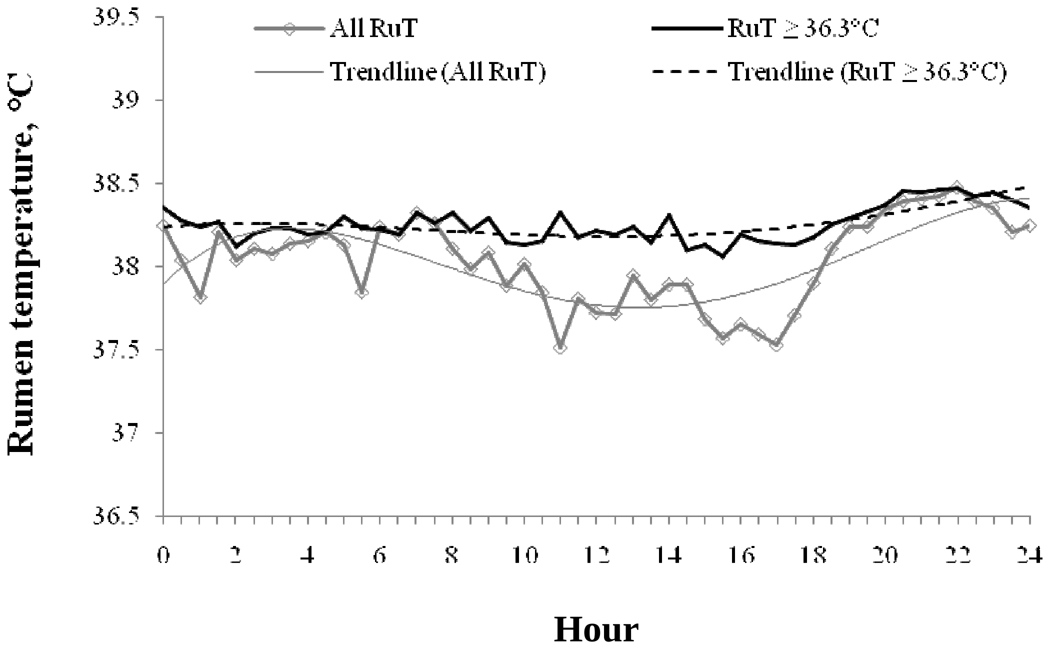

Figure 11. Mean hourly rumen temperature (RuT) of beef cows in December (n = 29) from 72 h before to 72 h after onset of estrus. Gray line is all RuT values, black line excludes values < 35.3°C (water drinking events). Hour 12 equals 1200 h.

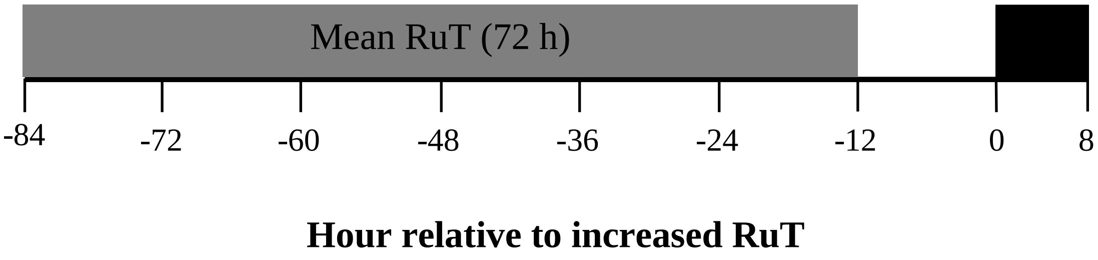

Figure 12. Detection of estrus in beef cows using increases in rumen temperature for any 8 h period (black box) compared with a pre-estrus average RuT for each cow calculated for a 72 h period that ended 12 h preceding the start of the 8 h increase used to identify estrus (gray box). Pre-estrus mean RuT included ≥ 24 RuT values and 8 h estrus identification periods include ≥ 4 RuT values.

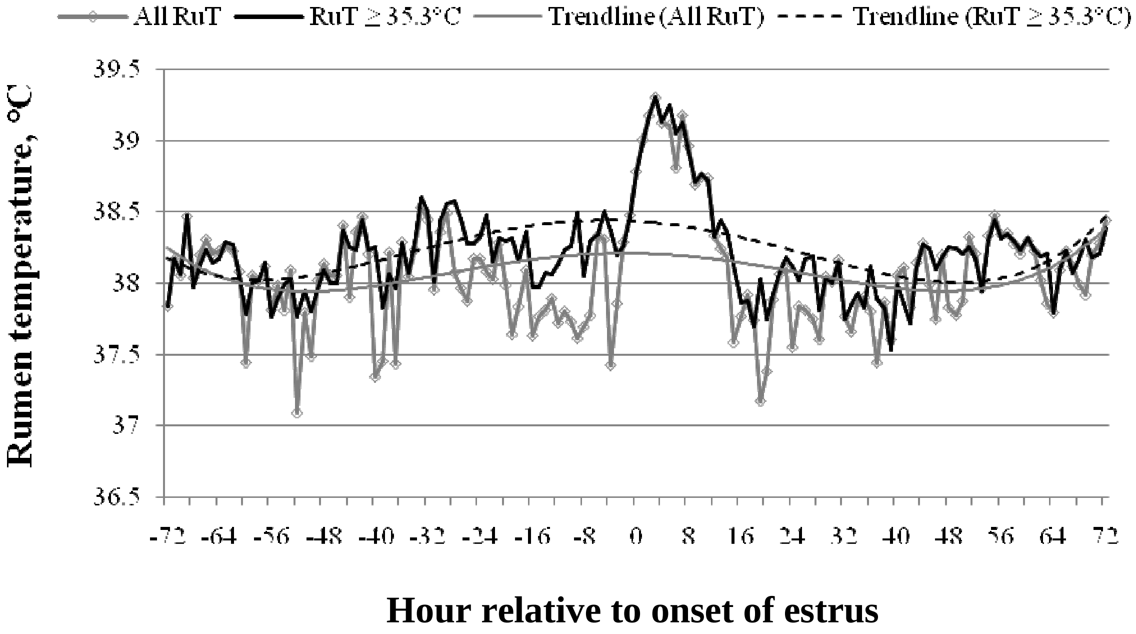

Figure 13. Mean rumen temperature (RuT) relative to onset of estrus (h 0) of beef cows in May. Gray line is all RuT values, black line excludes values < 35.3°C (water drinking events). Onset of estrus was determined with the HeatWatch® system.

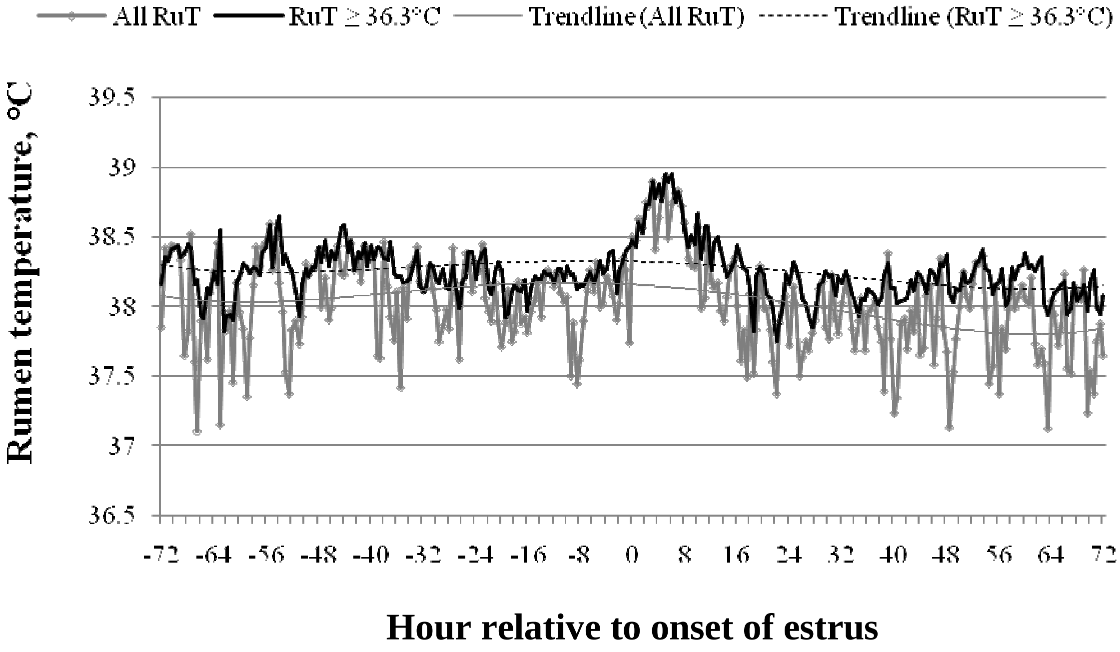

Figure 14. Mean rumen temperature (RuT) relative to onset of estrus (h 0) of beef cows in December. Gray line is all RuT values, black line excludes values < 35.3°C (water drinking events). Onset of estrus was determined with the HeatWatch® system.

Table 9. Mean rumen temperature (RuT; outlier values deleted) of cows during different periods relative to onset of estrus (0 h) compared with the same daily hours the day before or the day after estrus in May and December (Dec).

	Period[1]				
Item	Day before estrus	Around Estrus	Day after estrus	SE	*P* value
Hours in the period	-32 to -16	-8 to 8	16 to 32		
May RuT, °C	38.29^{a} (13)[2]	38.75^{b} (19)	37.96^{c} (18)	0.11	< 0.001
Dec RuT, °C	38.22^{a} (17)	38.54^{b} (22)	38.06^{a} (17)	0.08	< 0.001
Hours in the period	-28 to -20	-4 to 4	20 to 28		
May RuT, °C	38.23^{a} (16)	38.84^{b} (20)	37.99^{c} (22)	0.10	< 0.001
Dec RuT, °C	38.18^{a} (18)	38.52^{b} (26)	38.23^{a} (22)	0.07	< 0.004
Hours in the period	-24 to -16	0 to 8	24 to 32		
May RuT, °C	38.19^{a} (15)	39.24^{b} (17)	38.03^{a} (19)	0.12	< 0.001
Dec RuT, °C	38.25^{a} (18)	38.84^{b} (21)	38.15^{a} (19)	0.10	< 0.001

[1] Periods are hours relative to the onset of estrus (h 0) detected with HeatWatch®.

[2] Number of cows in each period are in parentheses.

[a, b, c] Means within a row without a common superscript differ ($P < 0.05$)

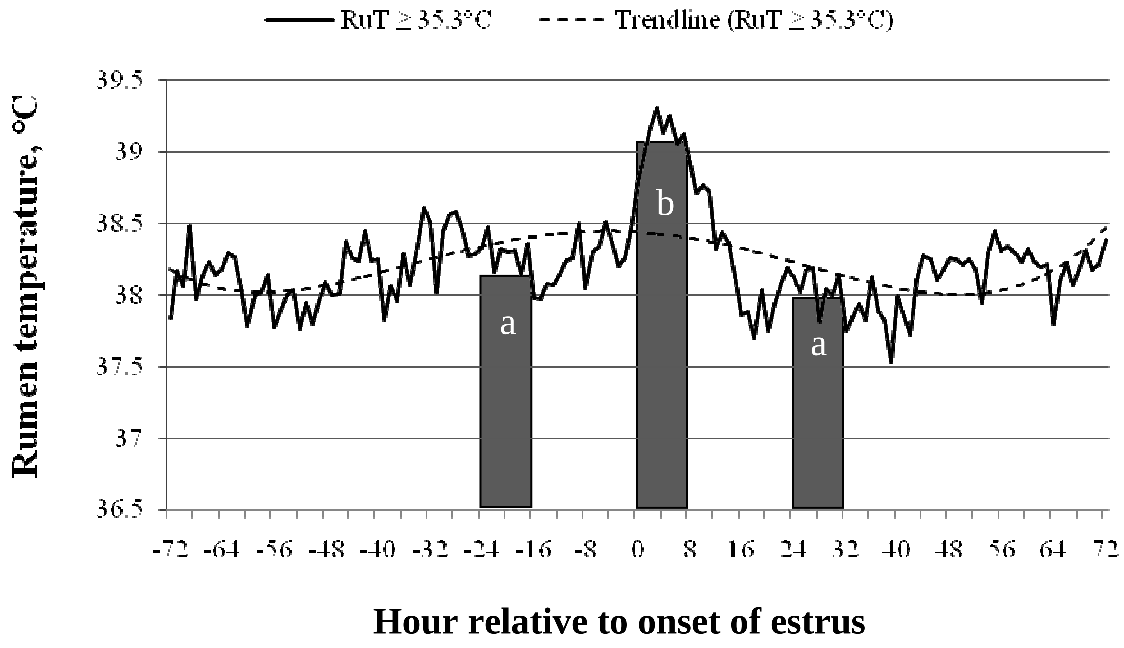

Figure 15. Mean rumen temperature (RuT) during the first 8 h after onset of estrus (h 0) compared with the same daily hours the day before and day after estrus of beef cows in May. Onset of estrus was determined with the HeatWatch® system. Rumen temperatures < 35.3°C are excluded (water drinking events). Bars represent mean RuT for 8 h after onset of estrus (39.24°C ± 0.12, n = 17) compared with the same daily hours the day before (38.19°C ± 0.09, n = 15) and the day after (38.03 °C ± 0.12, n = 19) estrus. $^{a, b}$ Means without a common subscript for periods differ ($P < 0.001$).

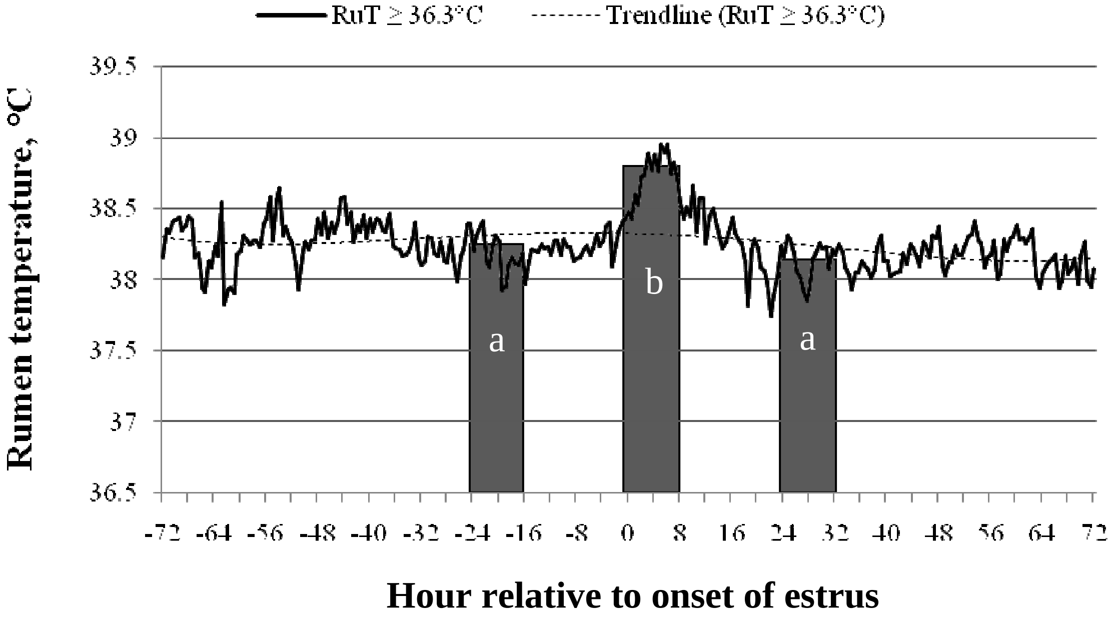

Figure 16. Mean rumen temperature (RuT) during the first 8 h after onset of estrus (h 0) compared with the same daily hours the day before and day after estrus of beef cows in December. Onset of estrus was determined with the HeatWatch® system. Rumen temperatures < 35.3°C are excluded (water drinking events).Bars represent mean RuT for 8 h after onset of estrus (38.84°C ± 0.11, n = 21) compared with the same daily hours the day before (38.25°C ± 0.09, n = 18) and the day after (38.15°C ± 0.10, n = 19) estrus. $^{a, b}$ Means without a common subscript for periods differ (*P* < 0.001).

Table 10. Detection of estrus in beef cows using increases in rumen temperature for any 8 h period compared with the pre-estrus average RuT for each cows in May and December.

	RuT increase[1]		
Item	≥ 0.3°C	≥ 0.5°C	≥ 0.7°C
May breeding season			
RuT increase correctly identified estrus	17/17[4]	17/17	17/17
RuT increase identified estrus in a non estrous cow	18/25[5]	4/25	1/25
RuT increase failed to identify estrus in estrous cow	0/17	0/17	0/17
December breeding season			
RuT increase correctly identified estrus	10/10[2]	8/10	7/10
RuT increase identified estrus in a non estrous cow	16/29[3]	3/29	0/29
RuT increase failed to identify estrus in estrous cow	0/10	2/10	3/10

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[1] Increases in mean RuT for any 8 h period of 0.3°C, 0.5°C or 0.7°C greater than the pre-estrus average for a cow calculated for a 72 h period that ended 12 h preceding the start of the 8 h increase used to identify estrus.

[2] Number of cows predicted/number of cows with RuT data at estrus (10 cows), 19 cows did not have adequate RuT vales during pre-estrus average calculation (< 24 h) and/or did not have adequate RuT values at estrus and 1 cow failed to record RuT data in December.

[3] Number of cows that increased above temperature parameter when cows were anestrous/number of cows with adequate RuT values during 72 h before to 72 h after estrus (29) during the December breeding season, 1 cow failed to record RuT data.

[4] Number of cows predicted/number of cows with RuT data at estrus (17 cows), 8 cows did not have adequate RuT vales during pre-estrus average calculation (< 24 h) and/or did not have adequate RuT values at estrus in May.

[5] Number of cows that increased above temperature parameter when cow was non-estrus/number of cows with adequate RuT values during 72 h before to 72 h after estrus (25) during the May breeding season.

Table 11. Mean rumen temperature (RuT; all values included) of cows during different periods relative to onset of estrus (0 h) compared with the same daily hours the day before or the day after estrus in May and December (Dec), including outlier values associated with water consumption

	Period[1]				
Item	Day before estrus	Around Estrus	Day after estrus	SE	*P* value
Hours in the period	-32 to -16	-8 to 8	16 to 32		
May RuT, °C	37.90^{a} (13)[2]	38.59^{b} (19)	37.77^{c} (18)	0.14	< 0.001
Dec RuT, °C	37.82^{a} (17)	38.35^{b} (22)	37.67^{a} (17)	0.13	< 0.001
Hours in the period	-28 to -20	-4 to 4	20 to 28		
May RuT, °C	37.93^{a} (16)	38.64^{b} (20)	37.73^{c} (22)	0.16	< 0.001
Dec RuT, °C	37.88^{a} (18)	38.45^{b} (26)	37.76^{a} (22)	0.12	< 0.001
Hours in the period	-24 to -16	0 to 8	24 to 32		
May RuT, °C	37.78^{a} (15)	39.05^{b} (17)	37.87^{a} (19)	0.17	< 0.001
Dec RuT, °C	37.85^{a} (18)	38.72^{b} (21)	37.76^{a} (19)	0.15	< 0.001

[1] Periods are hours relative to the onset of estrus (h 0) detected with HeatWatch®.

[2] Number of cows in each period are in parentheses.

$^{a, b, c}$ Means within a row without a common superscript differ ($P < 0.05$)

CHAPTER V

SUMMARY AND CONCLUSIONS

Researchers must continue to help farmers and ranchers improve the efficiency and profitability of beef production. Since maintenance energy requirements (MR) account for about 70% of the total energy required by cows (Ferrell and Jenkins, 1984), small improvements in energetic efficiency can drastically improve profitability, as feed is the highest variable cost in cattle production. Maintenance energy requirements varied 29% between the most and least efficient cows in our research and the amount of energy required for maintenance did not influence cow or calf performance. This supports that concept that selection for greater energetic efficiency is possible in beef cattle and that selection for more efficient cows will not negatively impact production output. Raising calves with heavier weaning weights on similar resources, or producing similar weaning weights with less feed input, will improve efficiency and sustainability of beef cattle production.

Inseminating cows to genetically superior bulls has the potential to enhance genetic traits and increase revenue. Artificial insemination can also shorten the calving season and therefore decrease labor costs if estrous synchronization is implemented. Estrous synchronization enhances the use of AI, increases the genetic potential to produce meat and milk, and can increase efficiency of beef and dairy production (Lauderdale, 2009). However, only 7.9% of beef cow-calf operations use estrous synchronization while 7.6% use AI (USDA, 2009). Time and/or labor are the primary reasons cited by producers for not using estrous synchronization or AI (USDA, 2009).

The ideal estrous detection system would provide continuous surveillance of cows, be accurate and automatically identify estrus, operate for the productive lifetime of the cow, and require minimal labor (Senger, 1994). This study provides evidence that RuT increased at estrus and has potential application to detect estrus in beef cows. Development of a real time RuT system for detection of estrus that is accurate and reliable offers advantages over current estrous detection systems. Rumen boluses allow frequent evaluation of body temperature with minimal impact on animal behavior. Decreasing labor associated with estrus detection while maintaining a high degree of accuracy will likely increase the use of AI in beef cows and improve the efficiency and profitability of beef operations.

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VITA

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Master of Science

Thesis: IDENTIFICATION OF MAINTENCE ENERGY REQUIREMENTS AND ESTRUS IN BEEF COWS

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Title of Study: IDENTIFICATION OF MAINTENCE ENERGY REQUIREMENTS AND ESTRUS IN BEEF COWS

Pages in Study: 119 Candidate for the Degree of Master of Science

Major Field: Animal Science

Scope and Method of Study: The effects of maintenance energy requirements (MR) on rumen temperature, postnatal calf growth, and concentrations of IGF-I, thyroxine (T_4), glucose and insulin in plasma were determined in spring calving Angus cows (n = 42). Nonlactating cows were individually fed a complete diet for 8 wk in amounts to supply MR (Level Model 1; NRC 1996). Cows were classified based on MR as low (**LMR**, n = 13; > 0.5 SD less than mean), moderate (**MMR**, n = 11; ± 0.5 SD of mean) or high (**HMR**, n = 8; > 0.5 SD greater than mean).

Angus cows, 4 to 8 yr of age, were used to evaluate changes in rumen temperature (RuT) associated with estrus. Temperature boluses (SmartStock, LLC) were placed in the rumen with a balling gun during gestation. Boluses were programmed to transmit RuT hourly. Estrus of cows was synchronized with $PGF_{2\alpha}$ at 79 ± 14 d after calving in May (n = 25) or 85 ± 22 d after calving in December (Dec, n = 30). The HeatWatch® Estrus Detection System (CowChips, LLC) was used to monitor onset of estrus. Increases in mean RuT for any 8 h period ≥ 0.3°C, ≥ 0.5°C or ≥ 0.7°C above the mean for a cow during 12 to 84 h preceding the 8 h increase were used as criteria to predict estrus.

Findings and Conclusions: Constant body weight (BW) was achieved for at least 17 d. Daily MR averaged 90.5 ± 5.3 $\text{Kcal}\cdot\text{kg BW}^{-0.75}\cdot d^{-1}$. There was a 29% difference in the amount of energy required for maintenance between the most and least efficient cows. Calf birth weight ($P = 0.89$), 205 d adjusted weaning weight ($P = 0.58$), and ADG from birth to weaning ($P = 0.58$) were not influenced by MR. Plasma concentrations of glucose, thyroxine and insulin were not influenced by MR; however IGF-I in plasma and RuT were influenced by MR. A combination of biomarkers may identify cows that require less energy to maintain BW.

Mean RuT during the first 8 h after onset of estrus was greater than RuT during 16 to 32 h before or after estrus in May and Dec ($P < 0.001$). An increase in RuT ≥ 0.3°C or ≥ 0.7°C correctly predicted estrus in 100% and 70% of estrous cows, respectively, in Dec; 100% of estrous cows in May were correctly predicted using either criterion. The use of RuT has potential application for detection of estrus in beef cows.

Keywords: beef cows, biomarker, estrus, maintenance requirement, rumen temperature

ADVISER'S APPROVAL: ______________________________