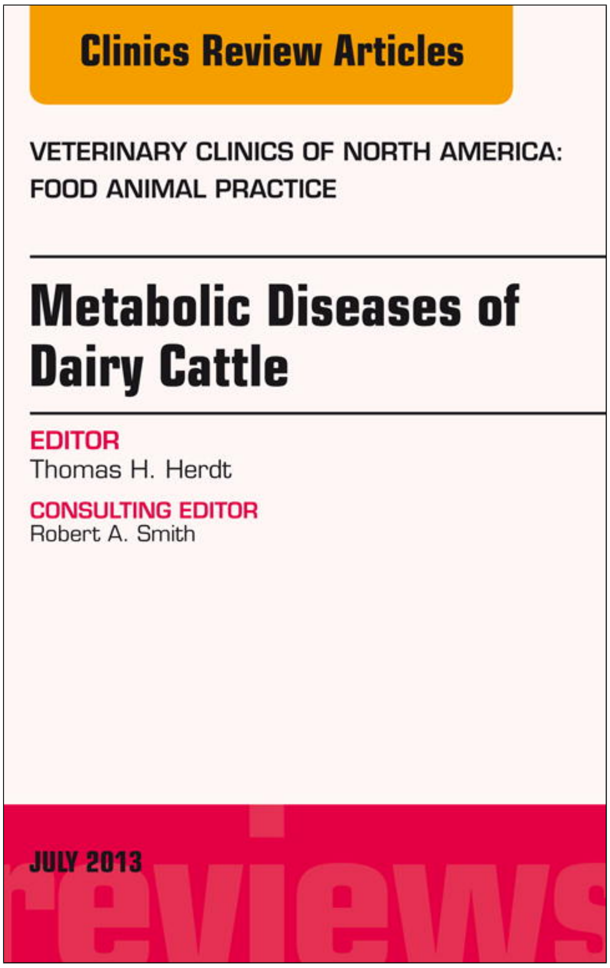

Clinics Review Articles
VETERINARY CLINICS OF NORTH AMERICA: FOOD ANIMAL PRACTICE
Metabolic Diseases of Dairy Cattle
EDITOR
Thomas H. Herdt
CONSULTING EDITOR
Robert A. Smith
JULY 2013
reviews

Energy and Protein Nutrition Management of Transition Dairy Cows

Ian J. Lean, BVSc, DVSc, PhD, MANZCVS[a,*],
Robert Van Saun, DVM, MS, PhD[b], Peter J. DeGaris, BVSc (Hons), PhD[c]

KEYWORDS

• Transition • Protein • Skeleton • Antioxidant • Vitamins

KEY POINTS

- The periparturient or transition period in the 4 weeks before and 4 weeks after calving is characterized by greatly increased risk of disease.
- The last 3 to 4 weeks of gestation are characterized by a period of rapid fetal growth, colostrogenesis and mammary development, and metabolic adjustments favoring mobilization of fat and other nutrients; all in combination with declining dry matter intake (DMI).
- The first 3 to 4 weeks after parturition features slowly increasing DMI in conjunction with rapidly increasing nutrient losses in support of milk production.

INTRODUCTION

The aims of this article and a companion article in this issue are to briefly review some of the underlying physiology of changes that occur around calving, examine the potential to control the risk of disease in this period, increase milk production, and improve reproductive performance through better nutritional management. Practical guidelines for veterinarians and advisors are provided.

The periparturient or transition period in the 4 weeks before and 4 weeks after calving is characterized by greatly increased risk of disease.[1–3] The last 3 to 4 weeks of gestation are characterized by a period of rapid fetal growth, colostrogenesis and mammary development, and metabolic adjustments favoring mobilization of fat and other nutrients; all in combination with declining dry matter intake (DMI). The first 3 to 4 weeks after parturition features slowly increasing DMI in conjunction with rapidly

[a] SBScibus, PO Box 660, Camden, New South Wales 2570, Australia; [b] Department of Veterinary & Biomedical Sciences, Pennsylvania State University, University Park, PA 16802, USA; [c] Tarwin Veterinary Group, 32 Anderson St, Leongatha, Victoria 3953, Australia
* Corresponding author.
E-mail address: ianl@sbscibus.com.au

Vet Clin Food Anim 29 (2013) 337–366
http://dx.doi.org/10.1016/j.cvfa.2013.03.005 vetfood.theclinics.com

increasing nutrient losses in support of milk production. During this time rapid mammary tissue growth continues as well as hypertrophy of key metabolic and digestive organs. Metabolically, the cow is in a state of nutrient reserve mobilization, primarily adipose and labile protein but also bone. A critical adaptation is to stabilize homeostatic control mechanisms of key nutrients including glucose and calcium in support of lactation. These adaptations to the demands of the fetus and lactation are a process termed homeorhesis.[4] Homeorhetic processes are the long-term adaptations to a change in state such as from being nonlactating to lactating or nonruminant to ruminant and involve an orchestrated series of changes in metabolism that allow an animal to adapt to the challenges of the altered state.

Diseases that result from disordered homeorhetic change reflect disorders in homeostasis, in other words, these are failures to adapt that result in shortages of nutrients that are vital for existence. These conditions are often interrelated[2,5,6] and include

- Hypocalcemia and downer cows
- Hypomagnesemia
- Ketosis, fatty liver, and pregnancy toxemia
- Udder edema
- Abomasal displacement
- Retained fetal membranes/metritis
- Poor fertility and poor production

Although in the past, there has been a tendency to look at metabolic systems in isolation, metabolic processes within the body are intricately linked. This concept reflects a need for effective homeostatic control of metabolism. A failure of one metabolic process inevitably affects the efficiency of others. As research progresses, homeostatic links between metabolic processes once believed to be distant and unrelated are continually uncovered. As a result of the increased understanding of homeostatic processes, the concept of transition feeding has evolved from one focused only on control of milk fever to an integrated nutritional approach that addresses optimization:

- Calcium and bone metabolism
- Energy metabolism
- Protein metabolism
- Immune function
- Rumen function

Addressing any one of these areas in isolation would be of some benefit, but developing integrated nutritional strategies based on an understanding of the homoeostatic and homeorhetic processes involved in the transition from a nonlactating to lactating animal would have substantial benefits.

Grummer[7] stated that “If transition feeding is important, then perturbations in nutrition during this period should affect lactation, health and reproductive performance.” There is now a substantial body of evidence clearly confirming that the transition period represents a brief but critically important period of time in a cow’s life when careful manipulation of diet can have a substantial impact on subsequent health and productivity. The aims of transition can be summarized in the establishment of 4 freedoms from the disorders outlined in **Table 1**.[8]

By achieving these goals, minimizing the loss of body protein before calving, and enhancing mammary development in the periparturient period, milk production will increase in the subsequent lactation. Although transition cow nutrition research results are not consistent across studies, milk production responses relative to controls are in

Table 1
Defining the 4 freedoms

Condition	Detail
Macromineral deficiency	Mainly refers to calcium, magnesium, and phosphorus. Milk fever and grass tetany (hypomagnesemia) can result from a conditioned deficiency whereby excess potassium reduces the capacity of the cow to maintain stable blood concentrations of calcium and magnesium
Lipid mobilization disorders	Includes ketosis, fatty liver, and pregnancy toxemia; diseases that are largely influenced by a failure to provide sufficient or effective energy sources around calving
Immune suppression	Often associated with lack of energy or protein intake; micronutrients are often involved including copper, selenium, zinc, and vitamins A, E, and D
Ruminal disruption	Cows are vulnerable to changes in diet resulting from lower feed intake, poor quality silages, and rapid introduction of concentrates after calving

the order of 500 to 1000 kg of milk per lactation with improved transition cow nutrition and management. Targets for the various disease conditions encountered during transition are outlined in **Table 2** and a framework for understanding the effects of transition and longer-term nutrition on reproduction is provided in **Fig. 1**.

This article takes a slightly different approach to providing suggestions regarding dietary requirements for the transition. In particular, the different sources of nonstructural carbohydrates are examined separately and fats are not treated generically. There is an increasing body of evidence that these are biologically active substances with marked differences in action. This article addresses aspects of lipid mobilization disorders and ruminal disruption. The focus is on meeting energy and protein needs while maintaining stable rumen function.

Definition: Negative energy balance refers to deficits in energy requirements that are estimated. A negative nutrient balance refers to the loss of body tissue consisting of fat, glycogen, protein, minerals, and vitamins that occurs around calving.

WHAT IS THE NATURE OF METABOLIC CHANGE AROUND CALVING?

Changes in hormone metabolism before calving have been well described.[4,9] Bauman and Currie[4] noted the following adaptive changes to lactation: increased lipolysis, decreased lipogenesis, increased gluconeogenesis, increased glycogenolysis, increased use of lipids and decreased glucose use as an energy source, increased mobilization of protein reserves, increased absorption of minerals and mobilization of mineral reserves, increased food consumption, and increased absorptive capacity for nutrients. Examining the homeorhetic and homeostatic responses to lactation assists understanding of the factors influencing the risk of disease. These responses can be exaggerated or perturbed by release of inflammatory mediators from lipid mobilization, environmental stressors, or subclinical disease conditions increasing postparturient disease risks.[10–14]

In brief, the following hormones influence the initiation of lactation and are associated with profound changes in metabolism. The precipitous decrease in plasma

Table 2
Achievable targets for cow health problems (expressed as the percentage of cases of calving cows within 14 days of calving)

Disease	Target (%)	Alarm Level (%)
Milk fever	1 (2 in old cows >8 y)	>3
Clinical ketosis	<1	>2
Subclinical ketosis >1 mmol/L (enzymatic assay week 1 after calving)	<10	>10
Retained placenta >6 h	<5	>7
Lameness >2 Specher et al locomotion score (1–5)	<4 when score >2	>4 when score >2
Clinical mastitis	<5 cases/100 cows in first 30 d	>5
Hypomagnesemia	0	Any
Calvings requiring assistance	<2	>3
Displaced abomasums (%)	<1	>2
Clinical acidosis (%)	<1	>1

progesterone levels that occurs at parturition is a key stimulus for lactogenesis. Estrogen levels increase rapidly in the last week of gestation and may play an important role in the initiation of lactation. Prolactin is important to the development of the mammary gland before lactation in cows. However, in dairy cattle, prolactin does not seem to play an important role in the maintenance of lactation. Glucocorticoids are important in the initiation and maintenance of lactation. Plasma cortisol levels increase in the immediate periparturient period and are associated with a transient hyperglycemia at calving.

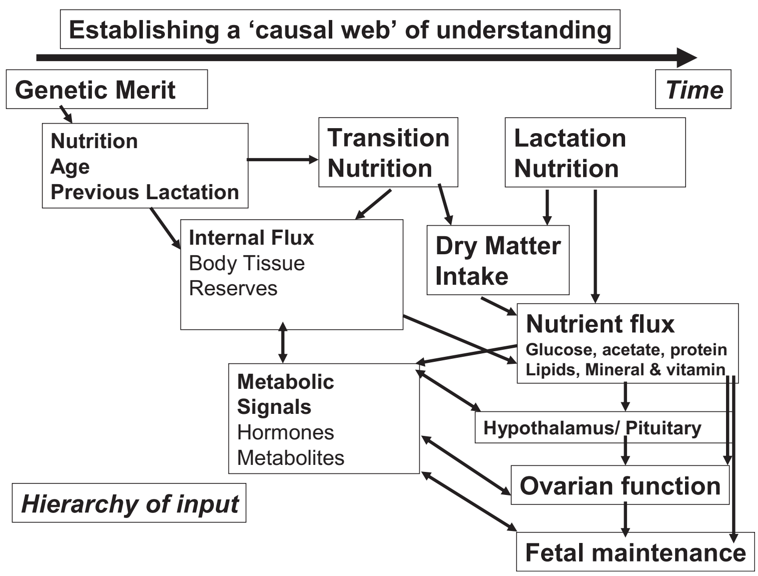


Fig. 1. A causal web to develop a model of metabolic subfertility in dairy cattle. The web shows a hierarchy of inputs and factors influencing subfertility. Nutrition before the dry period or initial calving and transition nutrition determine the nutrient stores available from body tissue reserves and those from lactation nutrition influence the nutrients available at any given time. These inputs, genetics, age, and environment determine reproductive responses. (*From* Lean IJ, Rabiee A. Quantitative metabolic and epidemiologic approaches to fertility of the dairy cow. In: Proceedings of the Dairy Cattle Reproduction Council. Denver (CO): 2007. p. 115–32.)

Insulin and glucagon play a central role in the homeostatic control of glucose. There is evidence, however, of insensitivity of cows to insulin in early lactation. The transitory hyperglycemia that occurs at calving does not seem to stimulate insulin. The insulin responses in hypoglycemic and ketonemic cows were less for glucose infusions and feeding than in normal cows, suggesting marked insulin resistance. Metz and van den Bergh[15] found that the response of adipose tissue to insulin in the periparturient cow was altered, because insulin addition did not reduce rates of lipolysis in vitro. Lipogenic activities of adipocytes are reduced by about one-third after calving. Glucagon plays a gluconeogenic role in the bovine, but may not stimulate lipolysis to the same extent as in nonruminant species. Thyroid hormone has a lactogenic function either when supplied orally or when injected and has been used in experimental protocols to induce ketosis.[16] However, thyroxine levels either decrease or are unchanged after calving.

Somatotropin plays a key lactogenic role in cattle as shown by milk production responses to exogenous somatotropin (rBST) and positive relationships between production and somatotropin levels in comparisons of high-yielding and low-yielding cattle. Somatotropin is possibly the most important hormonal determinant of increased milk yield in cattle. There is evidence that treatment with rBST may improve the health of periparturient cows, indicating the potential for somatotropin to positively integrate metabolism (see later discussion).

Fetal Demand for Nutrients

Bell[9] reviewed studies examining the nutrient demands of the fetus in late gestation. The fetal requirements for energy, although modest, are demanding in that the requirement for glucose is 4 times greater than that for acetate.

This demand highlights problems with the low energy density/low energy intake of dry cow diets recommended in the past. The fetus may even have an a priori demand for glucose as plasma glucose concentrations decreased in cows treated with sodium monensin before calving, despite the glucogenic action of monensin.[17]

The fetus also has significant requirements for amino acids, which are used for tissue deposition and oxidation. The fetal requirement for amino acids seems to be 3 times greater than the net requirement for fetal growth[9] because of significant oxidation of amino acids in the fetus.

In summary, fetal demands increase markedly in the last 4 weeks of gestation. There is an increased demand for glucose, an approximately 3-fold increase in demand for glucose immediately after calving, a doubling of the amino acid requirement, a 5-fold increase in fatty acid requirements, and a doubling of calcium needs in lactation compared with the needs of the cow and fetus.

CHALLENGES TO SUCCESSFUL ADAPTATION

Reduced Dry Matter Intake

Periparturient disease conditions are associated with decreased DMI, and feed intake is a critical determinant of health and productivity in the dry period. Feed intake and nutrient density of the diet determine the availability of nutrients to the cow and rapidly developing fetus. Grant and Albright[18] reviewed the feeding behavior and management factors during the transition period for dairy cattle and found that feed intake decreased by about 30% during the week before calving.

Factors that influence feed intake include social dominance, digestibility of the diet, access to feed, and palatability of the feed.[18] Cows and sheep with higher body condition scores have lower DMI after parturition,[19,20] and lower DMI has been noted immediately after calving and before calving[21] for cows with clinical ketosis.

Stephenson and colleagues[17] found that plasma 3-hydroxybutyrate (BHB) concentrations increased from 35 days before calving, in association with increased plasma free fatty acid concentrations (NEFA). Similar increases have been observed in other studies. It is unclear whether BHB and nonesterified fatty acid (NEFA) levels increase as a result of lower DMI, changes in the nutrient density of the diet, or increased fetal demand.

Providing access to feed for more than 8 hours per day and maintaining adequate availability and nutrient density of feed, controlling dominance behavior by grouping and providing adequate feed access and controlling body condition to an ideal of approximately 3.5 on the 5 point scale[22] reduce the risk of inadequate nutrient intake. In particular, the use of more digestible forages with lower slowly digestible fiber content allows greater DMI. Considerations around grouping of cattle need to be tempered with an understanding that movement of cattle between groups results in activity to establish new social hierarchies.[23–25]

The effect of greater DMI was demonstrated by force feeding periparturient cows through a ruminal fistula.[26] Cows that received more feed had less hepatic lipid accumulation and higher milk production after calving. The higher milk production resulted from greater postpartum feed intake and a highly significant positive correlation between precalving and postcalving feed intake was identified.[26] DMI before calving seems to be an important determinant of production after calving.

Impact of Lipid Mobilization on Liver Function

Reynolds and colleagues[27] measured glucose flux across portal-drained viscera over the transition period, finding minimal net change but a 267% increase in total splanchnic tissue output of glucose. This dramatic increase was almost exclusively a result of increased hepatic gluconeogenesis. Increased hepatic protein synthesis[9] and greater oxygen consumption[27] during transition are consistent with increased hepatic gluconeogenesis. The liver seems to be able to better synthesize glucose from propionate at 21 days postpartum compared with 1 day postpartum or 21 days prepartum.[28] The volatile fatty acid (VFA), propionate, is the primary source (50%–60%), of glucose but other substrates must be used to maintain glucose production, including lactate (15%–20%) from placental metabolism and skeletal muscle glycolysis, amino acids (20%–30%) from skeletal muscle catabolism and dietary absorption, and glycerol (2%–4%) released from adipose tissue lipolysis.[27,29]

Overton[30] examined the effects of lipid mobilization on liver function. Increased tissue mobilization increases the flux of NEFAs to the liver for oxidation and increases the need to export some of these back to peripheral tissues as ketones. The liver may not be able to reexport sufficient of these and accumulates fat in hepatocytes. The implications of this accumulation are that the rates of both gluconeogenesis and ureagenesis may be impaired.[31] Strang and colleagues[31] found that hepatic ureagenesis was reduced 40% through exposure of liver cells to NEFAs, which resulted in increased triglyceride accumulation similar to that of cows after calving. Triglyceride accumulation in the liver around the time of calving has been recognized for many years.[7,32]

Excessive lipolysis results in a greatly increased blood NEFA concentration and greater hepatic triglyceride accumulation and is associated with a higher risk of 1 or more periparturient diseases.[7,33–36] Any factor resulting in greater energy demand (eg, twin pregnancy, cold stress), lower energy intake (eg, poor feed quality, reduced feed availability, heat stress) or both decreases energy balance and ultimately blood NEFA concentration.[7]

In summary, maternal tissues reduce their use of glucose to meet energy needs over the transition, and increase hepatic gluconeogenesis to provide sufficient endogenous glucogenic substrate to account for lower nutrient intake. Failure to adapt to the demand for glucose increases mobilization of lipids and lipid-related disorders, such as hepatic lipidosis, ketosis, and pregnancy toxemia, the most severe of these.

ENERGY AND PROTEIN METABOLISM: OPPORTUNITIES AND LIMITATIONS TO IMPROVING PERFORMANCE

The demands for amino acids and glucose by the fetoplacental unit, and amino acids, glucose, and fatty acids by the mammary gland, particularly during stage 2 lactogenesis,[9,37] combine with a lowered potential DMI immediately before calving[38] to place the cow at great risk of mobilizing significant amounts of body fat and protein.

Energy Reserves: Body Condition

The body condition score (BCS) is a major determinant of the calving to first estrus interval; cows in higher body condition display estrus earlier.[19] Improved prepartum nutrition to increase BCS to moderate or better at calving was generally associated with increased milk production in dairy cows.[39–41] Excessive BCS (>3.75, scale of 1 to 5) in late pregnancy induces lower DMI during late pregnancy and early lactation resulting in greater negative energy balance in early lactation, as shown by excessive reduction in BCS (>1).[42] Westwood and colleagues[43] identified several factors that significantly influenced the display of estrus at first and second ovulation. Higher body weight of cattle before calving and postcalving appetite were significant factors that increased estrus display. Measures of metabolites in blood that reflected a better energy balance, including cholesterol concentrations and the ratio of glucose to 3-hydroxybutyrate, were also associated with greater display of estrus at ovulation.

In summary, improved BCS to approximately 3.75/5 is associated with better fertility, but greater increases are probably detrimental. The relationship between BCS and fertility may be better understood once the tissue components (fat, protein, glycogen) included in the BCS can be evaluated.

Energy Intake: Carbohydrates

The estimated energy balance after calving improves with increased energy density of the prepartum ration.[44–46] These improvements have been associated with trends toward increased milk production, lowered milk fat percentage, and significant increases in protein percentage and yield.[45] The effect of increased energy density of the prepartum diet, in particular increased fermentable carbohydrate concentration, may in part be mediated through increased development of rumen papillae in response to increased VFA production.[47] The increased absorptive capacity of the rumen may have reduced the risk of VFA accumulation and depression of rumen pH and the subsequent risk of acidosis in response to the feeding of high concentrate diets postpartum. Because adaptation and development of rumen papillae takes between 3 and 6 weeks,[48,49] the benefit of increasing exposure to a prepartum diet high in fermentable carbohydrate is likely to be curvilinear. There are also likely to be benefits associated with the prepartum adaptation of the rumen microflora to postpartum diets high in concentrates.[2] However, there is a challenge in controlling the risks of metabolic disease, particularly lipid mobilization disorders should cows become overconditioned. Overconditioning, however, is more a function of lactation diets than those in the dry period.

Acidosis

Part of the challenge is to provide diets appropriate to preparing the rumen for feeds of greater energy density, but controlling weight, particularly lipid, gain. Adaptation to feeds of higher energy density is important; in almost all production systems, there is a marked increase in exposure to starches and sugars at the time of calving. These increase the risk of acidosis, a relatively poorly understood condition. There are significant recent reviews and articles that advance our understanding of acidosis and the definition of acidosis. Although measures of rumen pH are often used for diagnosis, inconsistencies in cut-off thresholds that define acidosis severity have created confusion in the definition of acidosis.[50–52] Studies and definitions of acidosis based on area under the curve estimates of pH are likely sound; these have largely been conducted on limited numbers of fistulated cattle, therefore production outcomes such as milk production, weight gain for beef cattle, or lameness have not been associated with the cut-off points. There is a lack of studies that relate ruminal conditions to outcomes of acidosis or risk factors for acidosis, apart from diets deliberately designed to challenge rumen function; however, a few studies have provided a more detailed examination of acidosis based on large numbers of cattle. Bramley and colleagues,[53] Morgante and colleagues,[54] and O'Grady and colleagues[55] sampled 800, 120, and 144 head of dairy cattle, respectively, and investigated associations between diets and outcomes. All 3 studies provided similar findings of associations between low ruminal pH and a ruminal environment in which the levels of total VFA were increased, but propionate and valerate were particularly increased. Bramley and colleagues[53] found that approximately 10% of cows were in the group characterized by high ruminal concentrations of propionate, acetate, butyrate, valerate, and lactic acid, and low ammonia and pH, compared with other groups of cows. The least predictive variables for this group were pH and lactic acid concentrations and the most predictive were propionate and valerate concentrations. These cows had lower milk fat percentages and herds with a high prevalence of acidotic cows had a higher prevalence of lameness and diets lower in neutral detergent fiber and higher in nonfiber carbohydrates, suggesting that the categorization of these cows was sound.

It is unsurprising that pH was a poor predictive variable for acidosis in the field; the rumen is not homogeneous. Samples obtained by stomach tube, probably from the dorsal sac of the rumen, differ from those obtained using rumenocentesis by approximately 0.5 pH and are poorly related with r^2 of 0.2.[53] Golder and colleagues[56] examined the cut-off points for optimal sensitivity and specificity of use of rumen pH obtained using stomach tube or rumenocentesis in predicting acidosis. The optimal cut-off points for prediction of acidosis were less than 6.6 and less than 6.0 for stomach tube and rumenocentesis pH, respectively; however, neither provided a satisfactory test for acidosis, which was defined using the method of Bramley and colleagues.[53] The stomach tube pH had a sensitivity of 0.80 and a specificity of 0.76 and rumenocentesis pH had a sensitivity of 0.74 and a specificity of 0.79. It is likely, however, that testing groups of cows for pH less than 5.5, as advocated by Garrett and colleagues,[57] provides a satisfactory indicator of acidosis at the herd level.

The authors hypothesize that acidosis occurs along a continuum of ruminal conditions from subacute to peracute with different expressions of risk of acidosis reflecting the substrates available to the rumen. Similarly, it can be hypothesized that the risk of acidosis will vary depending on the length of exposure to rapidly fermentable diets, preformed acids in silage, and the type of fermentable substrate.

There are marked substrate differences in the risk of lactic acid generation and VFA production.[51,56] Simply, VFA and lactic acid formation is much more influenced by rapidly fermented substrates such as sugars rather than starches. Therefore, inclusion rates for starch and sugars should be considered separately; however, the recommendations in Table 3 are preliminary.

Protein Reserves: Body Condition

The importance of mobilized tissue protein as a source of amino acids for mammary metabolism and gluconeogenesis may be relatively small over the period from calving to peak lactation,[58] but is important in the first 1 to 2 weeks of lactation.[9] A reduction in skeletal muscle fiber diameter of 25% was observed immediately after calving[59] and a decline in the ratio of muscle protein to DNA was found in ewes during early lactation.[60] These findings support the concept that skeletal muscle is an important source of endogenous amino acids in early lactation. This hypothesis that improved protein and energy balance improves subsequent production is supported to some extent by the trend toward proportionally higher milk and protein yields in response to increasing days of exposure to a BioChlor-based (Church and Dwight, NJ) prepartum transition diet in younger cows, which are likely to have a greater energy and protein requirement to support growth (DeGaris, personal communication, 2010).

Table 3
Targets for diets: far off, transition, and fresh cows (first 40 days)

Diet Composition (% Dry Matter)	Dry Cows	Transition Cows	Fresh Cows
DMI[a]	1.75–2	2%–2.5%	3 to 4+
Neutral detergent fiber (NDF) (%)	>36	>36	>32
Physically effective NDF (%)	30	25–30	>19
Crude protein (CP) (%)	>12	14–16	16–19
Degradability of CP (%)	80	65–70	65–70
Estimated energy MCal (Nel)/kg MJ (ME)/kg	1.5 (1.33)[a] 10 (9)[a]	1.65 11	1.73–1.8 11.5–12
Estimated Nel (MCal/lb)	0.66 (0.60)	0.73	0.76–0.79
Starch (%)	Up to 18	16–20	24–26
Sugar (%)	Up to 4	4–6	6–8
Ether extract (%)	3	4–5	4–5
Calcium (%)	0.4	0.4–0.5	0.8–1.0
Phosphorus (%)	0.25	0.25	0.4
Magnesium (%)	0.3	0.45	0.3
DCAD (mEq/100 g)	0–25	−10	25–40
Selenium (mg/kg)	3	3	3
Copper (mg/kg)	10	15	20
Zinc (mg/kg)	40	48	48
Manganese (mg/kg)	12	15	15
Iodine (mg/kg)	0.6	0.6	0.6
Vitamin A (IU/kg)	2000	3200	3200
Vitamin D (IU/kg)	1000	2500	2500
Vitamin E (IU/kg)	15	30	15

Abbreviations: DCAD, dietary cation-anion difference; ME, metabolizable energy; Nel, net energy at lactation.
[a] Energy intake and content that is desirable varies with body condition.

Estimates of body protein reserves mobilized at calving are 25% to 27% of total body protein in a dairy cow, approximately 10 to 17 kg total.[61–63] Belyea and colleagues[61] noted that there was a significant variation in the abilities of cows to mobilize protein. Bell[9] estimated that a metabolizable protein (MP) deficit over 23 days after calving would be nearly 7 kg without accounting for gluconeogenic costs, and 12.5 kg with gluconeogenic costs included. These values seem consistent with previous studies. If 10 kg of protein was lost from muscle, this would equate to a loss of around 60 kg of muscle mass.

The proteins and ultimately amino acids mobilized are used for mammary milk protein synthesis and for gluconeogenesis in the liver to support lactation. It seems that the rates of mobilization of fat and protein are similar,[64,65] but there has been little recent work on the amounts of labile fat and protein in body tissue despite this being an important area of physiology. Given the amounts of body weight lost after calving, especially in cows of high body condition, we can be confident that the lipid reserves of these cows exceed the protein reserves. Vandehaar and St Pierre[66] highlighted the partitioning of energy to body weight observed by Oba and Allen[67] when lower neutral detergent fiber (NDF) diets were fed. It can be hypothesized that cattle exposed to such diets and achieving higher BCS will have greater start-up milk, but the internal flux of nutrients provided from tissue mobilization has a higher ratio, and almost certainly greater amounts of lipid compared with protein.

In summary, it is likely that the amount of labile protein is an important determinant of health. We can use a working assumption that diets that do not meet the MP needs of cattle and exceed energy needs in a previous lactation may place cows at greater risk of metabolic disorder.

Protein Intake Before Calving

Studies investigating optimal concentrations of dietary protein in prepartum diets have focused on crude protein (CP) content,[68–71] rumen degradable or rumen undegradable fractions in the diet,[69–72] but have not considered in depth the potential for ruminal microbial protein synthesis or MP balance. It has been suggested that by increasing prepartum protein body tissue reserves, the transition cow can better use these reserves after calving to support lactation and minimize metabolic disorders,[7,73] an effect possibly mediated through increased labile protein reserves. To examine the data in a systematic way, the authors conducted a meta-analysis of studies that have altered the protein content of feeds before calving. Briefly, a literature search of databases was conducted and the diets from 11 studies containing 26 comparisons were extracted. The following information was extracted: authors, year of publication, journal, study design, control and test protein levels, days before calving that the trial started and days in milk at trial end, rumen undegradable percentages, breed, number of milkings per day, feeding type, housing, parity, number of cows in control and treatment groups, DMI, milk yield (kg/cow/d), milk fat yield (kg/cow/d), milk fat percentage, milk protein yield (kg/cow/d), milk protein percentage, fat corrected milk and level corrected for energy corrected milk, average body weight, and measures of variance (standard error).

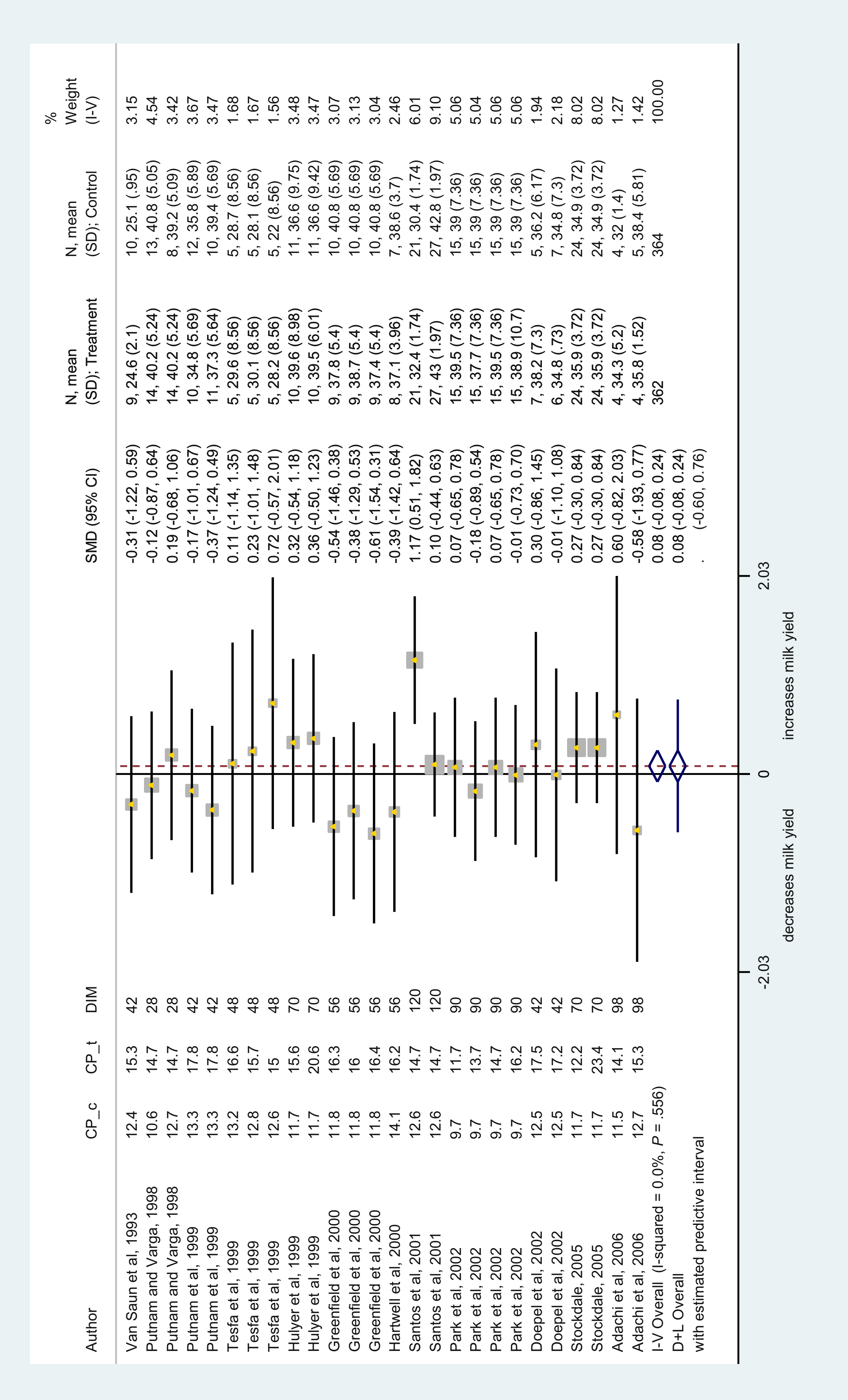
Fig. 2 displays a Forest plot of milk production results. In this plot, studies are identified and the size of the box is proportional to the weighting of the study within the meta-analysis. The extremities of the horizontal lines represent the 95% confidence intervals of the results for each comparison and diamonds represent the overall estimates using a fixed effect model using the inverse variance method (I-V Overall), and a random effects model using the inverse variance method of DerSimonan and Laird (D + L Overall). The results were homogeneous but were not significant, indicating that milk production was not increased with increased CP in the precalving diet. Further work is needed to evaluate these responses in terms of MP. A preliminary meta-analysis[8] found no relationship between MP yield and subsequent milk production, however the current database is larger and this matter will be revisited. A key consideration is that simply increasing CP may not increase MP and increasing the fermentability of the diet with starch may yield more MP than perhaps that achieved by increasing CP or even undegradable protein.

Nonetheless, prepartum diets with positive MP and energy balances may increase subsequent milk production by providing adequate substrate for fetal and mammary development. McNeil and colleagues[74] fed ewes in late gestation diets to meet estimated energy requirements and variable CP content (8%, 12%, and 15% CP). Ewes fed the low CP diet had fetuses nearly 20% less in weight compared with ewes fed the higher CP diet. Fetal weights were not different between the 12% and 15% CP diets, yet the ewes receiving the 12% CP diet lost maternal skeletal protein similar to the ewes fed the 8% CP diet. These data suggest some capacity exists for the placenta to sustain amino acid delivery to the fetus, but it is not unlimited in the face of more severe or sustained dietary protein insufficiency. Mammary development was greater in ewes on the higher CP diets. Similarly, increased BCS at calving, reflecting improved body tissue reserves, increased subsequent milk production.[19,75]

Data on the effect of prepartum protein on subsequent reproduction and health is scant. Overconditioned (>3.75 BCS) mature Holstein cows fed additional protein prepartum from animal protein bypass sources had decreased prevalence of ketosis and less health disorders.[76] These supplemented cows also had improved reproductive performance, similar to the effects seen in primiparous cows supplemented with additional bypass protein.[77] Better health was also observed in cows fed additional bypass protein or supplementation with rumen-protected methionine and lysine supplements prepartum until early lactation.[78] Increasing time exposure to a prepartum transition diet was found to improve the reproductive performance and health of cows in a grazing system.[79] Improved reproduction may result directly from protein status effects on oocyte development or quality, or may be secondary to decreased postpartum disease events or improved body condition and protein reserve status.

Mature cows fed a higher protein diet (14% CP) prepartum with supplemental methionine lost less body protein and had increased body fat in early lactation compared with cows consuming a diet with lower protein (11% CP).[80] Insulin is the primary mediator of nutrient use and its status and tissue sensitivity have been implicated in both disease risk and impaired reproduction. The revised quantitative insulin sensitivity check index (RQUICKI) calculation is a function of insulin, glucose, and NEFA concentrations and is inversely related to BCS.[81] Feeding additional bypass protein to dry mature cows increased RQUICKI values relative to BCS or score change[82] and values increased for mature cows fed balanced protein fractions in the diet compared with cows consuming a diet high in degradable protein.[83] Not all studies supplementing protein in prepartum diets have observed effects on health or reproduction; differences in dietary treatments, exposure time, protein source and amino acid balance, management factors, and many other interactions may have influences on this outcome.

Despite many anecdotal observations of increased calf birth weight and dystocia problems with increasing prepartum protein supplementation, controlled studies do not support a cause-and-effect response.[84] No differences in calf birth weights were seen when dairy heifers were fed protein in excess of prepartum NRC (National Research Council) recommendations.[77] Feeding additional protein (12% vs 14% CP) during the dry period did not increase calf birth weight (44.5 vs 42.2 kg) in mature Holstein cows.[76] However, heavier birth weights (47.1 kg) were observed in another


Author
CP_c
CP_t
DIM
SMD (95% CI)
N, mean (SD); Treatment
N, mean (SD); Control
% Weight (I-V)
Van Saun et al, 1993 12.4 15.3 42 -0.31 (-1.22, 0.59) 9, 24.6 (2.1) 10, 25.1 (.95) 3.15
Putnam and Varga, 1998 10.6 14.7 28 -0.12 (-0.87, 0.64) 14, 40.2 (5.24) 13, 40.8 (5.05) 4.54
Putnam and Varga, 1998 12.7 14.7 28 0.19 (-0.68, 1.06) 14, 40.2 (5.24) 8, 39.2 (5.09) 3.42
Putnam et al, 1999 13.3 17.8 42 -0.17 (-1.01, 0.67) 10, 34.8 (5.69) 12, 35.8 (5.89) 3.67
Putnam et al, 1999 13.3 17.8 42 -0.37 (-1.24, 0.49) 11, 37.3 (5.64) 10, 39.4 (5.69) 3.47
Tesfa et al, 1999 13.2 16.6 48 0.11 (-1.14, 1.35) 5, 29.6 (8.56) 5, 28.7 (8.56) 1.68
Tesfa et al, 1999 12.8 15.7 48 0.23 (-1.01, 1.48) 5, 30.1 (8.56) 5, 28.1 (8.56) 1.67
Tesfa et al, 1999 12.6 15 48 0.72 (-0.57, 2.01) 5, 28.2 (8.56) 5, 22 (8.56) 1.56
Hulyer et al, 1999 11.7 15.6 70 0.32 (-0.54, 1.18) 10, 39.6 (8.98) 11, 36.6 (9.75) 3.48
Hulyer et al, 1999 11.7 20.6 70 0.36 (-0.50, 1.23) 10, 39.5 (6.01) 11, 36.6 (9.42) 3.47
Greenfield et al, 2000 11.8 16.3 56 -0.54 (-1.46, 0.38) 9, 37.8 (5.4) 10, 40.8 (5.69) 3.07
Greenfield et al, 2000 11.8 16 56 -0.38 (-1.29, 0.53) 9, 38.7 (5.4) 10, 40.8 (5.69) 3.13
Greenfield et al, 2000 11.8 16.4 56 -0.61 (-1.54, 0.31) 9, 37.4 (5.4) 10, 40.8 (5.69) 3.04
Hartwell et al, 2000 14.1 16.2 56 -0.39 (-1.42, 0.64) 8, 37.1 (3.96) 7, 38.6 (3.7) 2.46
Santos et al, 2001 12.6 14.7 120 1.17 (0.51, 1.82) 21, 32.4 (1.74) 21, 30.4 (1.74) 6.01
Santos et al, 2001 12.6 14.7 120 0.10 (-0.44, 0.63) 27, 43 (1.97) 27, 42.8 (1.97) 9.10
Park et al, 2002 9.7 11.7 90 0.07 (-0.65, 0.78) 15, 39.5 (7.36) 15, 39 (7.36) 5.06
Park et al, 2002 9.7 13.7 90 -0.18 (-0.89, 0.54) 15, 37.7 (7.36) 15, 39 (7.36) 5.04
Park et al, 2002 9.7 14.7 90 0.07 (-0.65, 0.78) 15, 39.5 (7.36) 15, 39 (7.36) 5.06
Park et al, 2002 9.7 16.2 90 -0.01 (-0.73, 0.70) 15, 38.9 (10.7) 15, 39 (7.36) 5.06
Doepel et al, 2002 12.5 17.5 42 0.30 (-0.86, 1.45) 7, 38.2 (7.3) 5, 36.2 (6.17) 1.94
Doepel et al, 2002 12.5 17.2 42 -0.01 (-1.10, 1.08) 6, 34.8 (.73) 7, 34.8 (7.3) 2.18
Stockdale, 2005 11.7 12.2 70 0.27 (-0.30, 0.84) 24, 35.9 (3.72) 24, 34.9 (3.72) 8.02
Stockdale, 2005 11.7 23.4 70 0.27 (-0.30, 0.84) 24, 35.9 (3.72) 24, 34.9 (3.72) 8.02
Adachi et al, 2006 11.5 14.1 98 0.60 (-0.82, 2.03) 4, 34.3 (5.2) 4, 32 (1.4) 1.27
Adachi et al, 2006 12.7 15.3 98 -0.58 (-1.93, 0.77) 4, 35.8 (1.52) 5, 38.4 (5.81) 1.42
I-V Overall (I-squared = 0.0%, P = .556) 0.08 (-0.08, 0.24) 362 364 100.00
D+L Overall 0.08 (-0.08, 0.24)
with estimated predictive interval . (-0.60, 0.76)
-2.03
0
2.03
decreases milk yield
increases milk yield

group of mature Holstein cows with prolonged dry periods (>75 days) fed a low protein (9% CP) diet initially followed by a high protein (15% CP) diet during the last 4 weeks of gestation.[76] Sheep studies suggest that mid-gestation nutrition has greater potential to alter calf birth weight.[85]

Few studies have found prepartum dietary effects on colostrum quality. Greater immunoglobulin concentration in colostrum was observed in cows fed moderate (12% CP) or higher (14% CP) protein diets that contained animal product bypass protein sources compared with cows consuming a prepartum diet without supplemental bypass sources.[76] These immunoglobulin concentration differences in colostrum were the opposite of immunoglobulin concentrations measured in maternal serum over the last 4 weeks before calving. These observations might suggest an amino acid role in the transfer of immunoglobulins from maternal serum to colostrum.

In summary, excellent physiologic data suggest a need for diets that contain good levels of MP. The authors formulate diets that meet or exceed the MP requirements of CPM Dairy (Version 3.09). These diets require 14% to 16% CP and adequate starch and sugar as defined later (see **Table 3**).

Amino Acids

The balance and ratios of specific absorbed amino acids are of importance to production.[86,87] Methionine and lysine are often considered the first rate-limiting amino acids in support of lactation across a range of diets for dairy cows.[88] It is often assumed that methionine and lysine are also limiting amino acids for pregnancy, although no studies have validated this hypothesis. Methionine was added for the last 2 weeks of pregnancy for cows on high protein diets with bypass protein (39.6% CP) from animal sources and improved methionine availability to peripheral tissues was observed.[89] The investigators suggested that high bypass protein diets fed prepartum may restrict the contribution of microbial protein to MP. Histidine has been identified as a limiting amino acid, especially when most of the MP is derived from microbial protein.[90] Typical formulations for prepartum diets coupled with declining intake would result in microbial protein supplying more than 60% of MP delivered to the intestine.

Fig. 2. Forrest plot of the standardized mean difference of the effect of prepartum CP levels on postpartum milk production. Box size is proportional to the inverse variance of the estimates. The orange dot is the standardized mean difference or effect size of the trial. The horizontal lines represent the 95% confidence interval for the effect size. The solid vertical gray line represents a mean difference of zero or no effect. The diamonds represent the summary estimates using the fixed effect model (I-V overall) and the random effects model (D+L overall). The estimated predictive interval is of a future trial using the estimate of heterogeneity from the inverse variance effects. The figure shows that there was a positive but nonsignificant effect of changes in CP percentage in the diet fed before calving on postcalving milk production. Author refers to the first author and year of the publication. CP-c and CP-t refer to the CP content of rations in the control and treatment groups. DIM refers to days in milk. SMD is the standardized mean difference (standardized using the z-statistic). Thus, points to the left of the line represent a reduction in the parameter, whereas points to the right of the line indicate an increase. Each square represents the mean effect size for that study. The upper and lower limit of the line connected to the square represents the upper and lower 95% confidence interval for the effect size. The size of the square reflects the relative weighting of the study to the overall effect size estimate with larger squares representing greater weight. The dotted vertical line represents the overall effect size estimate. The diamond at the bottom represents the 95% confidence interval for the overall estimate. The solid vertical line represents a mean difference of zero or no effect.

The role of amino acid balance in peripartum diets has been studied intensively, although most emphasis has been placed on postpartum dietary effects relative to milk yield and component responses. Responses to rumen-protected methionine, lysine, or both in postpartum diets have been variable.[91] Modest milk yield and true protein yield responses are more often associated with methionine supplementation and in diets that may be marginal in meeting MP requirements.[92,93] The methionine response may be a result of its ability to support gluconeogenesis and liver fat transport compared with lysine. Variability in study findings may be attributed to confounding effects of dietary energy density (ie, microbial protein contribution), prepartum and postpartum protein content, DMI, and their interactions relative to potential response to amino acid supplementation. Study design can influence interpretation; the results of short-term Latin Square studies may be influenced by the cow's ability to mobilize body protein to mask treatment effects. Longer-term supplementation trials may minimize this impact. This effect is further complicated by prepartum dietary protein content and its effect on labile protein availability after calving. Higher prepartum protein diets lessened the impact of dietary protein manipulations after calving,[94] whereas lower prepartum protein diets accentuated the amino acid response.[72] In formulating postpartum diets, emphasis should be placed on providing sufficient MP with a balanced amino acid profile.

In summary, cows require amino acids. The balance needed is determined by their physiologic state. There is evidence for balancing diets for amino acids in support of early lactation, but less evidence for diets before calving. We recommend that prepartum diets should be formulated to meet or exceed MP requirements (CPM Version 3.09). The use of supplemental amino acids requires further study.

An alternative prepartum nutritional strategy

Although study results from Bertrics and colleagues[26] suggested that greater feed intake could reduce NEFA mobilization and decrease the risk for hepatic fatty infiltration, other studies indicated moderate feed intake could also show similar positive postpartum responses.[44,95–97] Cows moderately restricted in feed intake (80% of energy requirement) had lower NEFA concentrations precalving, less hepatic fat content, and greater postpartum intake. Ensuing studies suggested that energy consumption in the early dry period (>30 days before expected calving) also had significant effects on postpartum health and lactational performance.[96,98–101] Excessive energy intake may predispose the cow to greater maternal tissue insulin insensitivity coupled with the decline in physiologic insulin concentration that occurs just before calving, thus permitting more exaggerated NEFA mobilization and subsequent metabolic derangements. From these observations, a feeding management approach controlling total energy consumed and moderately restricting intake throughout the prepartum period has been advocated.[102]

The aim of these diets is to provide sufficient energy to meet daily needs and not supply excessive energy intake relative to NRC (2001) requirements.[88] Cereal straw forage or mature grass hay is used to dilute dietary energy provided from other more energy dense ingredients. These diets are typically corn silage based. Use of lactation-diet feed ingredients can be achieved by the dilution, allowing for easy adaptation to postpartum diets. Wheat straw is preferred because of its consistency and better NDF digestibility compared with other straw products. The bulking ingredient is used to allow for ad libitum intake rather than management attempting restricted intake. To be successful, the bulking ingredient should be properly incorporated into the diet and not fed separately. To ensure intake and to minimize sorting, the hay or straw should be chopped to achieve a consistent particle size of 4 to 6 cm (1.5–2 in). The straw or hay should be of high quality and palatable. An important aspect of the success of a controlled energy diet is ensuring adequate protein intake. Drackley and Janovick[102] recommend supplying more than 1000 g of MP, which can be achieved in diets formulated for 12% to 14% CP. To achieve postruminal delivery of this amount of MP, some bypass product sources of bypass protein will need to be included in the diet.

Use of controlled energy diets should be perceived as a complete dry cow program.[102] The use of straw typically controls dietary potassium concentration, thus reducing the risk of disrupted calcium homeostasis. Application of these diets in the field supports the contention that these diets can be successfully fed as single dry cow group systems, thus reducing some pen changes during transition. Research and field experience with these diets suggests reduced postpartum disease problems and potentially improved reproductive performance.[96,98,101,103] Similar health and production responses were seen in a series of studies using grass hay or wheat straw feeding either ad libitum or restricted.[104] Van Saun[76] used similarly formulated high fiber diets, but in a 2 group dry cow feeding program. Diets were formulated to provide either 1100 or 1300 g of MP per day to multiparous cows. Although the study cows were generally overconditioned (BCS >3.75/5), similar positive effects on health and reproduction were observed.

In summary, a key factor with prepartum DMI is to optimize intake in an effort to minimize any dramatic decline in intake just before calving. Significant intake declines stimulate greater NEFA mobilization, which adversely affects critical metabolic adaptations to lactation. Differing dry cow diet feeding strategies have been applied in the field with similar success, suggesting that other factors beyond nutrient content need to be considered. Grouping strategies, pen movements, environmental stressors, and feeding management play significant roles in the success or failure of any given dry cow feeding strategy.

Intake of Fats

Perhaps the most rapidly developing area of ruminant nutrition is that of fat nutrition. Recent understandings of the role of fats in metabolism open new avenues to improving metabolism, health, and reproduction in cattle. Studies have identified substantial potential for milk fats, including the conjugated linoleic acids (CLA), to positively influence human health[105] and along with this, increased understanding of the mechanisms by which different specific fatty acids in milk are generated. Critically, there is an increased awareness of the potential for specific dietary fats to improve health production and fertility. Vast differences (up to 15 standard deviations) in milk production and composition responses to different commonly used fats are observed.[106]

Lean and Rabiee[107] noted that there is a striking difference in the ration of lipid intake to milk yield for North American cows compared with Australasian cows; it can be estimated that lipid intake for North American cattle is about 15.5 g/L versus 20 to 22 g/L for the Australasian cows. Furthermore, for essential fatty acid (C18:2 and C18:3) intake at the duodenum, ratios are 0.7 g/L versus 1.4 to 1.6 g/L, respectively, or approximately half. These findings suggest support for the numerous pivotal roles identified for lipids in reproductive metabolism.[108,109]

Linoleic (C18:2) and linolenic fatty acids (C18:3) are classified as essential fatty acids and must be supplied in the diet, because the double bonds between the Δ-9-carbon and the terminal methyl group of the fatty acids cannot be produced by cattle. Roles for fatty acids include precursors for reproductive hormones (eg, prostaglandins), in membrane structures as phospholipids, and in immune function. The optimal requirement for 15% to 25% of energy being supplied as lipogenic precursors (or about 8% long-chain fatty acids in the diet) for efficient milk production was described.[110]

Although feeding fats during the prepartum and immediate postpartum period has not traditionally been recommended[111] because of the potential to reduce DMI, particularly in heifers,[42] there are now many studies in which beneficial effects have been observed.[112–115] These included a reduction in liver triglyceride accumulation[112] and levels of NEFA[113] in the immediate postpartum period and improved pregnancy rates.[116] Inclusion of fat in the diet may increase serum cholesterol concentrations,[117,118] a factor associated with better fertility. Westwood and colleagues[43] found that higher concentrations of plasma cholesterol were associated with a shorter interval from calving to conception, with greater probabilities of conception and successful pregnancy by day 150 of lactation, a finding consistent with those of Kappel and colleagues[119] and Ruegg and colleagues,[120] who found associations between cholesterol concentrations and fertility measures. Similarly, Moss[121] found that low blood cholesterol concentrations at mating were strongly associated with conception failure. However, fat feeding has a variable impact on the reproductive performance of lactating dairy cows with some positive[122–126] and some negative reports.[123,127,128] Reviews[109,129] have indicated that the effect of supplemental C18:2 from oil seeds and CaLCFA on fertility varied significantly, but suggest that supply of C18:2, C18:3, eicosapentaenoic acid (C20:5), and docosahexaenoic acid (C22:6) in forms that reach the lower gut, may have more profound effects on fertility.

Von Soosten and colleagues[130] elegantly explored the effects of protected CLA compared with a stearic acid–based fat supplement on tissue mobilization in a serial slaughter study. Overall, a trend for decreased body mass mobilization suggested a protective effect of CLA supplementation on the use of body reserves within 42 days in milk (DIM). Continuous CLA supplementation until 105 DIM increased body protein accretion. These effects suggested a more efficient use of metabolizable energy in CLA-supplemented early lactation dairy cows; an effect of ruminally protected fats not based solely on palm oil was identified independently in the meta-analysis of Rabiee and colleagues.[106]

The fat and fertility data require more research studies and meta-analytical evaluation that will include an evaluation of fat sources used and amounts and ratios of specific fats fed to elucidate the optimal approaches. However, de Veth and colleagues[115] demonstrated marked improvements (median time to conception was decreased by 34 days to 117 vs 151 DIM) in the fertility of cattle fed a ruminally protected CLA compared with cows not receiving the fat. Thatcher and colleagues[109] also found positive effects of supplementation with ruminally protected CLA and palm fatty acids on reproduction and health. Linolenic acid (C18:3) predominates in forage lipids,[131] however, concentrations of linoleic acid (C18:2) are also high in some pastures. It is possible that this and high digesta flow rates for cows on high-quality pasture diets may, in part, explain some of the differences in reproductive performance achieved in well-fed and well-managed pastured herds compared with NA (North American) herds. Data from Kay and colleagues[132] show that around 90% of *cis*-9, *trans*-11 CLA in milk is derived by endogenous synthesis of fats in fresh pasture. Studies in Ireland[133] found positive trends to a lower services per conception, but little overall effect of supplementation with protected CLA on fertility in cows on pasture, a finding consistent with the suggestions of Lean and Rabiee[107] that at least some of the differences in fertility of cows on pasture-based diets and those on total mixed ration diets may reflect the CLA generated from pasture.

In summary, fat supplements can improve energy balance, reduce the risk of metabolic diseases such as ketosis, and crucially allow energy density to be maintained in diets without increased dependence on rapidly fermentable carbohydrates. Evidence is increasing of a positive role for CLA, fed either as protected fats or derived from pasture in retaining body tissue after calving and improving fertility. Feeding fats in transition is an essential component of an integrated response to the challenges of needing to control tissue mobilization.

OTHER INTERVENTIONS

Somatotropin

Two actions of somatotropin increase the potential for rBST to improve periparturient health. The diabetogenic action of somatotropin, which decreases the sensitivity of peripheral tissues to insulin and increases blood glucose concentrations, increases the potential for treatment precalving to reduce the risk of ketosis. Administration of rBST to lactating cows is associated with insulin release[134] and liver function is also altered in cows treated with rBST resulting in increased gluconeogenesis.[135] Putnam and colleagues[70] fed cows 2 rations that differed in CP concentration (13.3% vs 17.8%) and treated cows with rBST every 14 days from 28 days before anticipated calving until parturition in a factorial study. Glucose concentrations tended to increase (P = .08) and the point directions were toward a decrease in NEFA and BHB concentrations for the rBST-treated cows both before and after calving. The rBST treatment significantly decreased concentrations of BHB before calving. Gulay and colleagues[136,137] found similar increases in glucose concentrations but NEFA concentrations were increased in cows treated with low doses of rBST before and after calving.

A second action is altered partitioning of nutrients in cows treated during a previous lactation. Lean and colleagues[138] treated 3 groups of cattle with different doses of rBST (17.2, 51.6 and 86 mg/d, respectively) during a previous lactation and found higher blood glucose, lower BHB, and lower NEFA concentrations in the treated cattle after calving. There are limited data to support routine use of rBST precalving to prevent lipid-related disorders but fundamental modes of action suggest a potential for benefit. Changes in body composition from rBST treatment in a previous lactation seem to be positive for health.

Methyl Donors

Hepatic fatty infiltration is an expected consequence of body lipid mobilization around the time of calving.[59,139] Excessive hepatic lipidosis results from an interaction between negative energy balance and acute phase inflammatory response, which reduces apoprotein synthesis, and is a significant precondition for many periparturient disease entities.[140] A limited supply of methionine and lysine may reduce production of very low density lipoprotein (VLDL) and predispose to hepatic lipidosis.[141,142] Choline and methionine metabolism are closely related and a significant percentage of methionine is used for choline synthesis.[143] Choline, a methyl donor and constituent of phosphatidylcholine, facilitates hepatic lipid export by increasing VLDL formation. Choline and methionine have interchangeable functions as methyl donors and may partially replace or spare the other.[144] Another methyl donor intermediate is betaine, an oxidative product of choline; recent research has not shown a beneficial response to its use in replacing methionine.[145]

Cows afflicted with either ketosis or hepatic lipidosis had lower serum apoproteins associated with VLDL structures, suggesting an inability of the liver to export triglycerides.[146] Similar to niacin, choline is readily degraded in the rumen, therefore a rumen-protected form is necessary for it to be efficacious when administered orally.[147] Early studies feeding increasing amounts of rumen-protected choline (treatments ranged from 0 to 20 g choline/d) showed a modest to no impact of choline on energy balance and liver triglyceride measurements.[148,149] In a controlled fatty liver induction study, feeding 15 g of choline per day during the induction phase reduced blood NEFA and liver triglyceride levels.[150] Feeding 15 g choline per day after induction of fatty liver tended to increase liver triglyceride clearance, which could contribute to improved performance[151] and health.[152,153] Liver triglyceride levels were reduced and glycogen content increased when choline was fed at 25 and 50 g/d prepartum (21 days) and postpartum (60 days), respectively.[154] Other recent preliminary studies found no response to choline supplementation, possibly attributed to lower BCSs and a lesser risk for negative energy balance.[155,156]

There is growing evidence suggesting that choline is a limiting nutrient for the high-producing dairy cow, especially around the time of calving.[144,157] However, the time frame of supplementation, dosage, BCS, dietary methionine status, and other factors may influence the response observed. A pooled study of choline supplementation before and after calving showed improved DMI and milk yield,[157] whereas a pooled analysis that included studies with only postpartum choline supplementation showed minimal effects on intake, milk yield, and composition.[158] There was no consistent finding of choline response measures of energy balance or any mechanism to explain the observed improvement in intake. If choline supplementation (15 g/d) starting prepartum can improve hepatic VLDL export and reduce fat accumulation, then improvement in hepatic function should reduce disease risk and increase performance.

Rumen Modifiers

There are few data available that specifically address the use of rumen modifiers, apart from monensin, in the transition period. The ionophore, sodium monensin, is widely used in dairy cattle production in the United States, Canada, Australasia, South America, South Africa. The effects of sodium monensin are primarily to increase ruminal propionate production, reflecting an increase in propionate-producing bacteria compared with those producing formate, acetate, lactate, and butyrate. There is a concomitant decrease in methane production from the rumen and a sparing effect on ruminal protein digestion.[159–162] The effects of monensin on blood metabolites, production, reproduction, and health were examined in a series of meta-analyses.[163–165] Data were obtained from up 59 articles and, in some cases, nearly 10,000 cows to provide more precise estimates of effect and to understand the sources of variance in the effects of this intervention. Monensin use in lactating dairy cattle significantly reduced blood concentrations of BHB by 13%, acetoacetate by 14%, and NEFA by 7%. Monensin increased blood glucose by 3% and urea by 6% but had no significant effect on cholesterol, calcium, milk urea, or insulin.

Monensin use in lactating dairy cattle significantly decreased DMI by 0.3 kg but increased milk yield by 0.7 kg and improved milk production efficiency by 2.5%. Monensin decreased milk fat percentage 0.13% but had no effect on milk fat yield; however, there was significant heterogeneity between studies for both of these responses. The percentage of milk protein was decreased by 0.03% but protein yield increased by 0.016 kg/d with treatment. Monensin increased the BCS by 0.03 and improved body weight change similarly (0.06 kg/d). These findings indicate a benefit of monensin for improving milk production efficiency while maintaining body condition. The effect of monensin on the percentage of milk fat and yield was influenced by diet.

Over all the trials analyzed,[163] monensin decreased the risk of ketosis (relative risk [RR] = 0.75), displaced abomasums (RR = 0.75), and mastitis (RR = 0.91). No significant effects of monensin were found for milk fever, lameness, dystocia, retained placenta, or metritis. Monensin had no effect on first-service conception risk (RR = 0.97) or days to pregnancy (hazard ratio = 0.93). However, the effect of monensin on dystocia, retained placenta, and metritis was variable. The causes of the variation were explored with meta-regression, indicating that longer periods of treatment with monensin before calving increased the risk of dystocia. Similarly, longer days of treatment before calving also increased the risk of retained placenta. Improvements in ketosis, displaced abomasums, and mastitis were achieved with monensin.

In summary, monensin use increased milk and milk protein production and the efficiency of production and reduced the risk of ketosis. Exposure to prolonged treatment in the dry period with monensin may increase the risk of dystocia and retained placenta, but treatment periods of around 3 weeks reduce the risk of these disorders. Monensin use reduces the risks of lipid mobilization disorders.

TOXINS

Endophyte Alkaloids and Other Mycotoxins

The effects of mycotoxins on cattle health in general have been documented and reviewed[166,167] but there are limited data on their effects specifically during the transition period when there is the potential for exacerbation of many of the challenges to successful adaptation to lactation.[168] The key effects of mycotoxins that may exacerbate the challenges faced during the transition period are altered rumen function, reduction in DMI, immunosuppression, and hepatotoxicity.

The rumen microflora and fauna provide an important first line of defense against some mycotoxins.[169] Orachatoxin, deoxynivalenol (DON), and, to a lesser extent, aflatoxin are metabolized to less toxic compounds in the rumen. Other mycotoxins seem to be unaffected by the rumen environment; fumonsins pass through the rumen virtually unchanged.[170] In contrast, zearalenone is metabolized to the more toxic α-zearalenol in the rumen.[169] Any alteration in rumen function is likely to increase the rate of ruminal bypass and intestinal absorption of mycotoxins usually detoxified by the rumen microbial flora and fauna.

Several mycotoxins have the ability to directly damage the rumen microbial mass. Patullin has an antibiotic activity against gram-positive and gram-negative bacteria as well as protozoa and has been shown to reduce cellulolysis of alfalfa hay, VFA production, and microbial protein synthesis.[171,172] The fusarium toxins, beauvericin and enniatin, also have an antibiotic effect against gram-positive bacteria and *Mycoplasma* spp.[173]

Ruminal acidosis may reduce the ability of the rumen to detoxify some mycotoxins. Sheep fed grain-based diets are less able to detoxify orachatoxin than those fed hay-based diets,[174] and cattle with subacute ruminal acidosis may be less able to detoxify DON.[168]

Any mycotoxicosis resulting in reduced rumen function or systemic disease will likely reduce DMI. Feed refusal of moldy feeds because of taste aversion is likely caused by contamination with microbial volatile organic compounds,[168] consisting of a wide range of volatile chemicals that are unpalatable to most species. The aerobic deterioration of ensiled feeds poses a particular risk. Bolsen and colleagues[175] demonstrated significant decreases in DMI as well as apparent digestibility of dry matter, organic matter, and NDF in cattle fed silage that consisted of 25% aerobically surface-spoiled silage. In addition, the investigators noted that rumen fiber mats in treated cattle were either partially or totally destroyed.

The immunosuppressive effects of many of the mycotoxins have long been recognized with even subclinical doses impairing the activity of B and T lymphocytes, antibody production, and macrophage and neutrophil function. Aflatoxins and trichothecenes can inhibit chemotaxis and phagocytosis of bovine neutrophils and macrophages,[176] and aflatoxins inhibit lymphoid cell proliferation and associated cytokines.[167] There is also evidence of synergistic inhibition of the immune system between aflatoxin and T-2 toxin.[177]

Several mycotoxins have been shown to be hepatotoxic. Sporodesmin, produced by *Pithomyces chartarum* growing in dead and decaying pastures during late summer and early autumn, causes facial eczema. This disease, mainly seen in the southern hemisphere, is characterized by hepatic photosensitization, reduced milk production, reproductive failure, and increased culling, particularly in cattle affected in the late dry period or early lactation. A negative effect on milk yield has been demonstrated in cattle treated with subclinical doses of sporodesmin.[178]

Perennial rye grasses may be high in the endophyte alkaloids ergovaline and lolitreme (and others). The presence of these alkaloids at increased levels may have extensive effects on production, reproduction, and the health of dairy cattle.[179] Although no studies have examined the effect of these alkaloids on cattle when fed specifically during the peripartum period, there are many potential pathways whereby a negative effect on subsequent productivity may be exerted. Random surveys of pastures in southwest Victoria, Australia, found levels of alkaloids in excess of those required to cause disease in cattle in approximately 30% of samples.[180]

In summary, despite the lack of specific data pertaining to the transition period, many mycotoxins have the potential to increase the risk of a poor transition. The authors, therefore, stress the need for careful attention to the state of silages used in the transition and the avoidance of poor feed quality. Even brief periods of inappetance pose a substantial health risk during transition.

RECOMMENDATIONS AND SUMMARY

Our recommendations for the diets are outlined in **Table 3** and in the companion article on minerals in this issue. Some of our recommendations will be refined by more work, particularly with regard to the role of protein nutrition over the gestation interval. There is a need to review the role of MP intake in the dry period on production, fertility, and health. The recent work on fat nutrition is clearly showing that fats are both powerful and different in their actions. The recommendations on these will be refined, as will specific recommendation for fiber and intake of nonfiber carbohydrate fractions.

In summary, dietary strategies should

- Ensure good protein stores (indicator BCS at calving >3.35/5)
- Avoid excessive adiposity (indicator BCS at calving <3.5) and
- Avoid abrupt dietary change to starch and sugars (starch 16%–20% before calving, 24%–26% after calving; sugars 4% before calving and 8% after calving)
- Provide high-quality proteins before and after calving (ie, positive MP diets)
- Avoid feed sources with spoilage (eg, silages that can put cows off feed)
- Use fats in transition diets, particularly ruminally protected CLA, unless pasture intakes are high

When combined with sensible mineral and dietary cation-anion difference strategies, these recommendations should result in better outcomes for cows and farmers.

ACKNOWLEDGMENTS

The authors thank Ms Veiss Harvey and Dr Ahmad Rabiee for the meta-analysis information provided.

REFERENCES

1. Shanks L. Postpartum distribution of costs and disorders of health. J Dairy Sci 1981;64:683–8.

2. Curtis CR, Erb EH, Sniffen CJ, et al. Path analysis of dry period nutrition, postpartum metabolic and reproductive disorders, and mastitis in Holstein cows. J Dairy Sci 1985;68:2347–60.
3. Stevenson MA, Lean IJ. Culling in eight New South Wales dairy herds: part 1. Descriptive epidemiology. Aust Vet J 1998;76:482–8.
4. Bauman DE, Currie WB. Partitioning of nutrients during pregnancy and lactation: a review of mechanism involving homeostasis and homeorhesis. J Dairy Sci 1980;63:1514–29.
5. Curtis CR, Erb EH, Sniffen CJ. Association of parturient hypocalcemia with eight periparturient disorders in Holstein cows. J Am Vet Med Assoc 1983;183:559–61.
6. Curtis MA. Epidemiology of uterine infections in dairy cows. Antioxidant and metabolic investigations. PhD thesis. Sydney: University of Sydney; 1997.
7. Grummer RR. Impact of changes in organic nutrient metabolism on feeding the transition dairy cow. J Anim Sci 1995;73:2828–33.
8. Lean IJ, DeGaris PJ, Wade LK, et al. Transition management of dairy cows: 2003. In: Parkinson TJ, editor. Proceedings of the Australian & New Zealand Combined Dairy Veterinarians' Conference. Taupo (New Zealand): Foundation for Continuing Education of the N.Z. Veterinary Association; 2003. p. 221–48.
9. Bell AW. Regulation of organic nutrient metabolism during transition from late pregnancy to early lactation. J Anim Sci 1995;73:2804–19.
10. Bernabucci U, Ronchi B, Lacetera N, et al. Influence of body condition score on relationships between metabolic status and oxidative stress in periparturient cows. J Dairy Sci 2005;88:2017–26.
11. Bertoni G, Trevisi E, Han X, et al. Effects of inflammatory conditions on liver activity in puerperium period and consequences for performance in dairy cows. J Dairy Sci 2008;91:3300–10.
12. Trevisi E, Amadori M, Cogrossi S, et al. Metabolic stress and inflammatory response in high-yielding periparturient dairy cows. Res Vet Sci 2012;93:695–704.
13. Zebeli Q, Sivaraman S, Dunn SM, et al. Intermittent parenteral administration of endotoxin triggers metabolic and immunological alterations typically associated with displaced abomasum and retained placenta in periparturient dairy cows. J Dairy Sci 2011;94:4968–83.
14. Bradford BJ, Mamedova LK, Minton E, et al. Daily injection of tumor necrosis factor-alpha increases hepatic triglycerides and alters transcript abundance of metabolic genes in lactating dairy cattle. J Nutr 2009;139:1451–6.
15. Metz SH, Van Den Bergh SG. Regulation of fat mobilization in adipose tissue of dairy cows in the period around parturition. Neth J Agr Sci 1977;25:198–211.
16. Hibbitt KG. The induction of ketosis in the lactating dairy cow. J Dairy Res 1966;33:291–8.
17. Stephenson KA, Lean IJ, Hyde ML, et al. Effects of monensin on the metabolism of periparturient dairy cows. J Dairy Sci 1997;80:830–7.
18. Grant RJ, Albright JL. Feeding behavior and management factors during the transition period in dairy cattle. J Anim Sci 1996;73:2791–803.
19. Garnsworthy PC, Topps JH. The effect of body condition of dairy cows at calving on their food intake and performance when given complete diets. Anim Prod 1982;35:113–9.
20. Cowan RT, Robinson JJ, McDonald I, et al. Effects of body fatness at lambing and diet in lactation on body tissue loss, feed intake and milk yield of ewes in early lactation. J Agr Sci 1980;95:497–514.

21. Lean IJ, Bruss ML, Trout HF, et al. Bovine ketosis and somatotropin: risk factors for ketosis and effects of ketosis on health and production. Res Vet Sci 1994;57:200–9.
22. Edmondson AJ, Lean IJ, Weaver LD, et al. A body condition scoring chart for Holstein dairy cows. J Dairy Sci 1989;72:68–78.
23. Cook NB, Nordlund KV. Behavioral needs of the transition cow and considerations for special needs facility design. Vet Clin North Am Food Anim Pract 2004;20:495–520.
24. Hosseinkhani A, DeVries TJ, Proudfoot KL, et al. The effects of feed bunk competition on the feed sorting behavior of close-up dry cows. J Dairy Sci 2008;91:1115–21.
25. Proudfoot KL, Veira DM, Weary DM, et al. Competition at the feed bunk changes the feeding, standing, and social behavior of transition dairy cows. J Dairy Sci 2009;92:3116–23.
26. Bertics SJ, Grummer RR, Cadorniga-Valino C, et al. Effect of prepartum dry matter intake on liver triglyceride concentration and early lactation. J Dairy Sci 1992; 75:1914–22.
27. Reynolds CK, Aikman PC, Lupoli B, et al. Splanchnic metabolism of dairy cows during the transition from late gestation through early lactation. J Dairy Sci 2003; 86:1201–17.
28. Drackley JK, Overton TR, Douglas GN. Adaptations of glucose and long-chain fatty acid metabolism in liver of dairy cows during the periparturient period. J Dairy Sci 2001;84:E100–12.
29. Overton TR, Waldron MR. Nutritional management of transition dairy cows: strategies to optimize metabolic health. J Dairy Sci 2004;87(Suppl E):E105–19.
30. Overton TR, Piepenbrink MS. Managing metabolism of transition cows through nutrition. In: Proceedings of the 36th Pacific Northwest Animal Nutrition Conference. Seattle (WA), 2001.
31. Strang BD, Bertics SJ, Grummer RR, et al. Effect of long-chain fatty acids on triglyceride accumulation, gluconeogenesis, and ureagenesis in bovine hepatocyctes. J Dairy Sci 1998;81:728–39.
32. Roberts CJ, Reid IM, Rowlands GJ, et al. A fat mobilisation syndrome in dairy cows in early lactation. Vet Rec 1981;108:7–9.
33. Holtenius P, Hjort M. Studies on the pathogenesis of fatty liver in cows. Bov Pract 1990;25:91.
34. Dyke PB, Emery RS, Liesman JL, et al. Prepartum nonesterified fatty acids in plasma are higher in cows developing periparturient health problems [abstract]. J Dairy Sci 1995;78(Suppl 1):264.
35. Kaneene JB, Miller RA, Herdt TH, et al. The association of serum nonesterified fatty acids and cholesterol, management and feeding practices with peripartum disease in dairy cows. Prev Vet Med 1997;31:59–72.
36. LeBlanc SJ, Leslie KE, Duffield TF. Metabolic predictors of displaced abomasum in dairy cattle. J Dairy Sci 2005;88:159–70.
37. Tucker HA. Endocrine and neural control of the mammary gland. In: Larson BL, editor. Lactation. Ames: Iowa State University Press; 1985. p. 39.
38. Marquardt JP, Horst RL, Jorgensen NA. Effect of parity on dry matter intake at parturition in dairy cattle. J Dairy Sci 1977;60:929–34.
39. Rogers GL, Grainger C, Earle DF. Effect of nutrition of dairy cows in late pregnancy on milk production. Aust J Exp Agric Anim Husb 1979;19:7–12.
40. Domecq JJ, Skidmore AL, Lloyd JW, et al. Relationships between body condition scores and milk yield in a large dairy herd of high yielding Holstein cows. J Dairy Sci 1997;80:101–12.

41. Waltner SS, McNamara JP, Hillers JK. Relationships of body condition score to production variables in high producing Holstein dairy cattle. J Dairy Sci 1993;76:3410–9.
42. Hayirli A, Grummer RR, Nordheim EV, et al. Animal and dietary factors affecting feed intake during the prefresh transition period in Holsteins. J Dairy Sci 2002;85:3430–43.
43. Westwood CT, Lean IJ, Garvin JK. Factors influencing fertility of Holstein dairy cows: a multivariate description. J Dairy Sci 2002;85:3225–37.
44. Holcomb CS, Van Horn HH, Head HH, et al. Effects of prepartum dry matter intake and forage percentage on postpartum performance of lactating dairy cows. J Dairy Sci 2001;84:2051–8.
45. Minor DJ, Trower SL, Strang BD, et al. Effect of nonfibre carboydrate and niacin on periparturient metabolic status and lactation of dairy cows. J Dairy Sci 1998;81:189–200.
46. Grum DE, Drackley JK, Younker RS, et al. Nutrition during the dry period and hepatic lipid metabolism of periparturient dairy cows. J Dairy Sci 1996;79:1850–64.
47. Dirksen G, Liebich HG, Mayer K. Adaptive changes of the ruminal mucosa and functional and clinical significance. Bov Pract 1985;20:116–20.
48. Kauffold P, Voiqt J, Piatkowski B. Studies of the influence of nutritional factors on the ruminal mucosa. 1. Structure and functional state of the ruminal mucosa after feeding of extreme rations and abrupt change in nutrition. Arch Tierernahr 1975;25:247–56 [in German].
49. Dirksen G, Dori S, Arbel SA, et al. The rumen mucosa - its importance as a metabolic organ of the high producing dairy cow. Israel J Vet Sci 1997;52:73–9.
50. Kleen JL, Hooijer GA, Rehage J, et al. Subacute ruminal acidosis (SARA): a review. J Vet Med A Physiol Pathol Clin Med 2003;50:406–14.
51. Nagaraja TG, Titgemeyer EC. Ruminal acidosis in beef cattle: the current microbiological and nutritional outlook. J Dairy Sci 2007;90:E17–38.
52. Plaizier JC, Krause DO, Gozho GN, et al. Subacute ruminal acidosis in dairy cows: the physiological causes, incidence and consequences. Vet J 2008;176:21–31.
53. Bramley E, Lean IJ, Fulkerson WJ, et al. The definition of acidosis in dairy herds predominantly fed on pasture and concentrates. J Dairy Sci 2008;91:308–21.
54. Morgante M, Stelletta C, Berzaghi P, et al. Subacute rumen acidosis in lactating cows: an investigation in intensive Italian dairy herds. J Anim Physiol Anim Nutr 2007;91:226–34.
55. O'Grady L, Doherty ML, Mulligan FJ. Subacute ruminal acidosis (SARA) in grazing Irish dairy cows. Vet J 2008;176:44–9.
56. Golder HM, Celi P, Rabiee AR, et al. Effects of grain, fructose, and histidine on ruminal pH and fermentation products during an induced subacute acidosis protocol. J Dairy Sci 2012;95:1971–82.
57. Garrett EF, Pereira MN, Nordlund KV, et al. Diagnostic methods for the detection of subacute ruminal acidosis in dairy cows. J Dairy Sci 1999;82:1170–8.
58. Bauman DE, Elliot JM. Control of nutrient partitioning in lactating ruminants. In: Mepham TB, editor. Biochemistry of lactation. Amsterdam: Elsevier; 1983. p. 437.
59. Reid IM, Roberts CJ, Baird GD. The effects of underfeeding during pregnancy and lactation on structure and chemistry of bovine liver and muscle. J Agr Sci 1980;94:239–45.
60. Smith RW, Knight KA, Walsh A. Effects of lactation on the concentration of protein, lipids and nucleic acids in ovine skeletal muscle. Res Vet Sci 1981;30:253–4.

61. Belyea RL, Frost GR, Martz FA, et al. Body composition of dairy cattle by potassium-40 scintillation detection. J Dairy Sci 1978;61:206–11.
62. Botts RL, Hemken RW, Bull LS. Protein reserves in the lactating cow. J Dairy Sci 1979;62:433–40.
63. Parquay R, De Baere R, Lousse A. The capacity of the mature cow to lose and recover nitrogen and the significance of protein reserves. Br J Nutr 1972;27: 27–37.
64. Oldham JD, Emmans GC. Prediction of responses to protein and energy yielding nutrients. In: Nutrition and lactation in the dairy cow. Proceedings of the 46th University of Nottingham Easter School in Agricultural Sciences. London, 1988. p. 76–96.
65. Baldwin RL, France J, Gill M. Metabolism of the lactating cow. I. Animal elements of a mechanistic model. J Dairy Res 1987;54:77–105.
66. VandeHaar MJ, St-Pierre N. Major advances in nutrition: relevance to the sustainability of the dairy industry. J Dairy Sci 2006;89:1280–91.
67. Oba M, Allen MS. Effects of brown midrib 3 mutation in corn silage on productivity of dairy cows fed two concentrations of dietary neutral detergent fiber: 1. Feeding behavior and nutrient utilization. J Dairy Sci 2000;83:1333–41.
68. Putnam DE, Varga GA. Protein density and its influence on metabolite concentration and nitrogen retention by Holstein cows in late gestation. J Dairy Sci 1998;81:1608–18.
69. Huyler MT, Kincaid RL, Dostal DF. Metabolic and yield responses of multiparous Holstein cows to prepartum rumen-undegradable protein. J Dairy Sci 1999;82: 527–36.
70. Putnam DE, Varga GA, Dann HM. Metabolic and production responses to dietary protein and exogenous somatotropin in late gestation dairy cows. J Dairy Sci 1999;82:982–95.
71. Greenfield RB, Cecava MJ, Johnson TR, et al. Impact of dietary protein amount and rumen degradability on intake, prepartum liver triglyceride, plasma metabolites and milk production in transition dairy cattle. J Dairy Sci 2000;83:703–10.
72. Wu Z, Fisher RJ, Polan CE, et al. Lactation performance of cows fed low or high ruminally undegradable protein prepartum and supplemental methionine and lysine postpartum. J Dairy Sci 1997;80:722–9.
73. Van Saun RJ. Dry cow nutrition: the key to improved fresh cow performance. Vet Clin North Am Food Anim Pract 1991;7:599–620.
74. McNeill DM, Ehrhardt RA, Slepetis R, et al. Protein requirement of sheep in late pregnancy: partitioning of nitrogen between conceptus and maternal tissues. J Anim Sci 1997;75:809–81.
75. Boisclair Y, Grieve DG, Stone JB, et al. Effect of prepartum energy, body condition and sodium bicarbonate on production of cows in early lactation. J Dairy Sci 1986;69:2636–47.
76. Van Saun RJ. Effects of undegradable protein fed prepartum on subsequent lactation, reproduction, and health in Holstein dairy cattle. PhD thesis. Ithaca: Cornell University; 1993.
77. Van Saun RJ, Idleman SC, Sniffen CJ. Effect of undegradable protein amount fed prepartum on postpartum production in first lactation Holstein cows. J Dairy Sci 1993;76:236–44.
78. Xu S, Harrison JH, Chalupa WH, et al. The effect of ruminal bypass lysine and methionine on milk yield and composition of lactating cows. J Dairy Sci 1998; 81:1062–77.

79. DeGaris PJ, Lean IJ, Rabiee AR, et al. Effects of increasing days of exposure to pre-partum diets on reproduction and health in dairy cows. Aust Vet J 2010;88: 84–92.
80. Philips GJ, Citron TL, Sage JS, et al. Adaptations in body muscle and fat in transition dairy cattle fed differing amounts of protein and methionine hydroxy analog. J Dairy Sci 2003;86:3634–47.
81. Holtenius P, Holtenius K. A model to estimate insulin sensitivity in dairy cows. Acta Vet Scand 2007;49:29–31.
82. Van Saun RJ. Insulin sensitivity measures in dry dairy cows and relationship to body condition score. In: Proceedings of the 14th International Congress of Production Diseases in Farm Animals. Ghent (Belgium): 2010.
83. Van Saun RJ. Insulin sensitivity measures in lactating dairy cows and relationship to body condition score. In: Proceedings of the 26th World Buiatrics Congress Santiago. Chile: 2010.
84. Rice LE. Dystocia-related risk factors. Vet Clin North Am Food Anim Pract 1994; 10:53–68.
85. Bell AW. Influence of maternal nutrition and other factors on calf birth weight. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. Syracuse (NY): 2004. p. 159–65.
86. Rulquin J, Verite R. Amino acid nutrition of dairy cows: production effects and animal requirements. In: Garnsworthy PC, Cole DJ, editors. Recent advances in animal nutrition. Nottingham (United Kingdom): University Press; 1993. p. 55.
87. Sniffen CJ, Chalupa WH, Ueda T, et al. Amino acid nutrition of the lactating dairy cow. In. Proceedings of the Cornell Nutrition Conference. Rochester: 2001. p. 188–97.
88. Board on Agriculture and Natural Resources. Nutrient requirements of dairy cattle. 7th edition. Washington, DC: National Academy Press; 2001.
89. Bach A, Huntington GB, Stern MD. Response of nitrogen metabolism in preparturient dairy cows to methionine supplementation. J Dairy Sci 2000;78:742–9.
90. Lee C, Hristov AN, Cassidy TW, et al. Rumen-protected lysine, methionine, and histidine increase milk protein yield in dairy cows fed a metabolizable protein-deficient diet. J Dairy Sci 2012;95:6042–56.
91. Robinson PH. Impacts of manipulating ration metabolizable lysine and methionine levels on the performance of lactating dairy cows: a systematic review of the literature. Livest Sci 2010;127:115–26.
92. Patton RA. Effect of rumen-protected methionine on feed intake, milk production, true milk protein concentration, and true milk protein yield, and the factors that influence these effects: a meta-analysis. J Dairy Sci 2010;93: 2105–18.
93. Ordway RS, Boucher SE, Whitehouse NL, et al. Effects of providing two forms of supplemental methionine to periparturient Holstein dairy cows on feed intake and lactational performance. J Dairy Sci 2009;92:5154–66.
94. Socha MT, Putnam DE, Garthwaite BD, et al. Improving intestinal amino acid supply of pre- and postpartum dairy cows with rumen-protected methionine and lysine. J Dairy Sci 2005;88:1113–26.
95. Grum DE, Drackley JK, Younker RS, et al. Production, digestion, and hepatic lipid metabolism of dairy cows fed increased energy from fat or concentrate. J Dairy Sci 1996;79:1836–49.
96. Douglas GN, Overton TR, Bateman HG, et al. Prepartal plane of nutrition, regardless of dietary energy source, affects periparturient metabolism and dry matter intake in Holstein cows. J Dairy Sci 2006;89:2141–57.

97. Agenas A, Burstedt E, Holtenius K. Effects of feeding intensity during the dry period. 1. Feed intake, body weight, and milk production. J Dairy Sci 2003; 86:870–82.
98. Dann HM, Morin DE, Murphy MR, et al. Prepartum intake, postpartum induction of ketosis, and periparturient disorders affect the metabolic status of dairy cows. J Dairy Sci 2005;88:3249–64.
99. Dann HM, Litherland NB, Underwood JP, et al. Diets during far-off and close-up dry periods affect periparturient metabolism and lactation in multiparous cows. J Dairy Sci 2006;89:3563–77.
100. Janovick NA, Drackley JK. Prepartum dietary management of energy intake affects postpartum intake and lactation performance by primiparous and multiparous Holstein cows. J Dairy Sci 2010;93:3086–102.
101. Janovick NA, Boisclair YR, Drackley JK. Prepartum dietary energy intake affects metabolism and health during the periparturient period in primiparous and multiparous Holstein cows. J Dairy Sci 2011;94:1385–400.
102. Drackley JK, Janovick NA. Controlled energy diets for dry cows. In: Proceedings of the Western Dairy Management Conference. Reno. (NV): 2007. p. 7–16.
103. Beever DE. The impact of controlled nutrition during the dry period on dairy cow health, fertility and performance. Anim Reprod Sci 2006;96:212–26.
104. Litherland NB, Weich WD, Lobao D, et al. Prepartum feeding strategies for greater postpartum success. In: Proceedings of the Minnesota Nutrition Conference. Owatonna (MN): 2012. p. 18–9.
105. Parodi PW. Conjugated linoleic acid and other anticarcinogenic agents of bovine milk fat. J Dairy Sci 1999;82:1339–49.
106. Rabiee AR, Breinhild K, Scott W, et al. Effect of fat additions to diets of dairy cattle on milk production and components: a meta-analysis and meta-regression. J Dairy Sci 2012;95:3225–47.
107. Lean IJ, Rabiee A. Quantitative metabolic and epidemiological approaches to fertility of the dairy cow. In: Proceedings of the Dairy Cattle Reproduction Council. Denver (CO): 2007. p. 115–32.
108. Staples CR, Burke JM, Thatcher WW. Influence of supplemental fats on reproductive tissues and performance of lactating cows. J Dairy Sci 1998;81:856–71.
109. Thatcher WW, Bilby TR, Bartolome JA, et al. Strategies for improving fertility in the modern dairy cow. Theriogenology 2006;65:30–44.
110. Kronfeld DS. The potential importance of the proportions of glucogenic, lipogenic and aminogenic nutrients in regard to the health and productivity of dairy cows. Fortschr Tierphysiol Tierernahr 1976;(7):3–26.
111. Santos JE, Juchem SO, Galvao KN, et al. Transition cow management to reduce metabolic disease and improve reproductive management. Adv Dairy Tech 2003;15:287–304.
112. Selberg KT, Staples CR, Badinga L. Production and metabolic responses to dietary conjugated linoleic acid (CLA) and trans-octadecenoic acid isomers in periparturient dairy cows [abstract]. J Dairy Sci 2002;85(Suppl 1):19.
113. Doepel L, Lapierre H, Kennelly JJ. Peripartum performance and metabolism of dairy cows in response to prepartum energy and protein intake. J Dairy Sci 2002;85:2315–34.
114. Jones B, Fish RD, Martin A, et al. Case study: effects of supplemental linoleic and linolenic acids on reproduction in Holstein cows. Prof Anim Sci 2008;24:500–5.
115. De Veth MJ, Bauman DE, Koch W, et al. Efficacy of conjugated linoleic acid for improving reproduction: a multi-study analysis in early-lactation dairy cows. J Dairy Sci 2009;92:2662–9.

116. Frajblat M. Metabolic state and follicular development in the post-partum lactating dairy cow. PhD thesis. Ithaca: Cornell University; 2000.
117. Grummer RR, Carroll DJ. A review of lipoprotein cholesterol metabolism: importance to ovarian function. J Anim Sci 1988;66:3160–73.
118. Chilliard Y. Dietary fat and adipose tissue metabolism in ruminants, pigs, and rodents: a review. J Dairy Sci 1993;76:3897–931.
119. Kappel LC, Ingraham RH, Morgan EB, et al. Relationship between fertility and blood glucose and cholesterol concentrations in Holstein cows. Am J Vet Res 1984;45:2607–12.
120. Ruegg PL, Goodger WJ, Holmberg LD, et al. Relation among body condition score, serum urea nitrogen and cholesterol concentrations, and reproductive performance in high-producing Holstein dairy cows in early lactation. Am J Vet Res 1992;53:10–4.
121. Moss N. The epidemiology of subfertility in Australian dairy cows. PhD thesis. Sydney: University of Sydney; 2001.
122. Burke JM, Carroll DJ, Rowe KE, et al. Intravascular infusion of lipid into ewes stimulates production of progesterone and prostaglandin. Biol Reprod 1996; 55:169–75.
123. Carroll DJ, Hossain FR, Keller MR. Effect of supplemental fish meal on the lactation and reproductive performance of dairy cows. J Dairy Sci 1994;77:3058–72.
124. Ferguson JD, Sklan D, Chalupa WV, et al. Effects of hard fats on in vitro and in vivo rumen fermentation, milk production, and reproduction in dairy cows. J Dairy Sci 1990;73:2864–79.
125. Sklan D, Moallem U, Folman Y. Effect of feeding calcium soaps of fatty acids on production and reproductive responses in high producing lactating cows. J Dairy Sci 1991;74:510–7.
126. Son J, Grant RJ, Larson LL. Effects of tallow and escape protein on lactational and reproductive performance of dairy cows. J Dairy Sci 1996;79:822–30.
127. Sklan D, Kaim M, Moallem U, et al. Effect of dietary calcium soaps on milk yield, body weight, reproductive hormones, and fertility in first parity and older cows. J Dairy Sci 1994;77:1652–60.
128. Lucy MC, Staples CR, Thatcher WW, et al. Influence of diet composition, dry-matter intake, milk production and energy balance on time of post-partum ovulation and fertility in dairy cows. Anim Prod 1992;54:323–31.
129. Thatcher WW, Santos JE, Staples CR, et al. The science of Omega-3 fatty acids on dairy cows reproduction. In: J Dairy Sci ADSA Series. Quebec (Canada): 2002.
130. von Soosten D, Meyer U, Piechotta M, et al. Effect of conjugated linoleic acid supplementation on body composition, body fat mobilization, protein accretion, and energy utilization in early lactation dairy cows. J Dairy Sci 2012;95:1222–39.
131. Palmquist DL, Jenkins TC. Fat in lactation rations: review. J Dairy Sci 1980;63: 1–14.
132. Kay JK, Mackle TR, Auldist MJ, et al. Endogenous synthesis of cis-9, trans-11 conjugated linoleic acid in dairy cows fed fresh pasture. J Dairy Sci 2004;87: 369–78.
133. Hutchinson I, de Veth MJ, Stanton C, et al. Effects of lipid-encapsulated conjugated linoleic acid supplementation on milk production, bioenergetic status and indicators of reproductive performance in lactating dairy cows. J Dairy Res 2011;78:308–17.
134. Bines JA, Hart IC, Morant SV. Endocrine control of energy metabolism in the cow: the effect on milk yield and levels of some blood constituents of injecting growth hormone and growth hormone fragments. Br J Nutr 1980;43:179–88.

135. Pocius PA, Herbein JH. Effects of in vivo administration of growth hormone on milk production and in vitro hepatic metabolism in dairy cattle. J Dairy Sci 1986;69:713–20.
136. Gulay MS, Garcia AN, Hayen MJ, et al. Responses of Holstein cows to different bovine somatotropin (bST) treatments during the transition period and early lactation. Asian-Australian Journal of Animal Sciences 2004;17:784–93.
137. Gulay MS, Hayen MJ, Liboni M, et al. Low doses of bovine somatotropin during the transition period and early lactation improves milk yield, efficiency of production, and other physiological responses of Holstein cows. J Dairy Sci 2004;87:948–60.
138. Lean IJ, Troutt HF, Bruss ML, et al. Postparturient metabolic and production responses in cows previously exposed to long-term treatment with somatotropin. J Dairy Sci 1991;74:3429–45.
139. Bobe G, Young YW, Beitz DC. Pathology, etiology, prevention, and treatment of fatty liver in dairy cows. J Dairy Sci 2004;87:3105–24.
140. Ametaj BN. A new understanding of the causes of fatty liver in dairy cows. Adv Dairy Tech 2005;17:97–112.
141. Durand D, Chilliard Y, Bauchart D. Effects of lysine and methionine on in vivo hepatic secretion of VLDL in the high yielding dairy cow [abstract]. J Dairy Sci 1992;75(Suppl 1):279.
142. Gruffat D, Durand D, Graulet B, et al. Regulation of VLDL synthesis and secretion in the liver. Reprod Nutr Dev 1996;36:375–89.
143. Emmanuel B, Kennelley JJ. Kinetics of methionine and choline and their incorporation into plasma lipids and milk components in lactating goats. J Dairy Sci 1984;67:1912–8.
144. Pinotti L, Baldi A, Dell'Orto V. Comparative mammalian choline metabolism with emphasis on the high-yielding dairy cow. Nutr Res Rev 2002;15:315–31.
145. Davidson B, Hopkins BA, Odle J, et al. Supplementing limited methionine diets with rumen-protected methionine, betaine, and choline in early lactation Holstein cows. J Dairy Sci 2008;91:1552–9.
146. Oikawa S, Katoh N, Kawawa F, et al. Decreased serum apolipoprotein B-100 and A-1 concentrations in cows with ketosis and left displacement of the abomasum. Am J Vet Res 1997;58:121–5.
147. Atkins KB, Erdman RA, Vandersall JH. Dietary choline effects on milk yield and duodenal choline flow in dairy cattle. J Dairy Sci 1988;71:109–16.
148. Hartwell JR, Cecava MJ, Donkin SS. Impact of dietary rumen undegradable protein and rumen-protected choline on intake, peripartum liver triacylglyceride, plasma metabolites and milk production in transition dairy cows. J Dairy Sci 2000;83:2907–17.
149. Piepenbrink MS, Overton TR. Liver metabolism and production of cows fed increasing amounts of rumen-protected choline during the periparturient period. J Dairy Sci 2003;86:1722–33.
150. Cooke RR, Silva del Rio N, Caraviello DZ, et al. Supplemental choline for prevention and alleviation of fatty liver in dairy cattle. J Dairy Sci 2007;90:2413–8.
151. Pinotti L, Baldi A, Politis I, et al. Rumen-protected choline administration to transition cows: effects on milk production and vitamin E status. J Vet Med A Physiol Pathol Clin Med 2003;50:18–21.
152. Zom RL, van Baal J, Goselink RM, et al. Effect of rumen-protected choline on performance, blood metabolites, and hepatic triacylglycerols of periparturient dairy cattle. J Dairy Sci 2001;94:4016–27.

153. Lima FS, Sa Filho MF, Greco LF, et al. Effects of feeding rumen-protected choline on incidence of diseases and reproduction of dairy cows. Vet J 2012; 193:140–5.
154. Elek P, Newbold JR, Gaal T, et al. Effects of rumen-protected choline supplementation on milk production and choline supply of periparturient dairy cows. Animal 2008;1:1595–601.
155. Oelrichs WA, Lucy MC, Kerley MS, et al. Feeding soybeans and rumen-protected choline to dairy cows during the parturient period and early lactation: effects on plasma lipid balance [abstract]. J Dairy Sci 2004;87(Suppl):441.
156. Janovick-Guretzky NA, Carlson DB, Garrett JE, et al. Lipid metabolite profiles and milk production for Holstein and Jersey cows fed rumen-protected choline during the periparturient period. J Dairy Sci 2006;89:188–200.
157. Grummer RC. Choline: a limiting nutrient for transition dairy cows. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. Syracuse (NY): 2012. p. 16–8.
158. Sales J, Homolka P, KoukolovÃ¡ V. Effect of dietary rumen-protected choline on milk production of dairy cows: a meta-analysis. J Dairy Sci 2010;93:3746–54.
159. Bergen WG, Bates DB. Ionophores: their effect on production efficiency and mode of action. J Anim Sci 1984;58:1465–83.
160. Richardson LF, Raun AP, Potter EL, et al. Effect of monensin on rumen fermentation in vitro and in vivo. J Anim Sci 1976;43:657–64.
161. Russell JB, Strobel HJ. Effect of ionophores on ruminal fermentation. Appl Environ Microbiol 1989;55:1–6.
162. Van Nevel CJ, Demeyer DI. Effect of monensin on rumen metabolism in vitro. Appl Environ Microbiol 1977;34:251–7.
163. Duffield TF, Rabiee AR, Lean IJ. A meta-analysis of the impact of monensin in lactating dairy cattle. Part 3. Health and reproduction. J Dairy Sci 2008;91: 2328–41.
164. Duffield TF, Rabiee AR, Lean IJ. A meta-analysis of the impact of monensin in lactating dairy cattle. Part 2. Production effects. J Dairy Sci 2008;91:1347–60.
165. Duffield TF, Rabiee AR, Lean IJ. A meta-analysis of the impact of monensin in lactating dairy cattle. Part 1. Metabolic effects. J Dairy Sci 2008;91:1334–46.
166. Osweiler GD. Mycotoxins - Contemporary issues of food animal health and productivity. Vet Clin North Am Food Anim Pract 2000;16:511–30.
167. Oswald IP, Marin DE, Bouhet S, et al. Immunotoxicological risk of myoctoxins for domestic animals. Food Addit Contam 2005;22:354–60.
168. Fink-Gremmels J. The role of mycotoxins in the health and performance of dairy cows. Vet J 2008;176:84–92.
169. Kiessling KH, Pettersson H, Sandholm K, et al. Metabolism of aflatoxin, ochratoxin, zearalenone and three trichothecenes by intact rumen fluid, rumen protozoa and rumen bacteria. Appl Environ Microbiol 1984;47:1070–3.
170. Caloni F, Spotti M, Auerbach H, et al. In vitro metabolism of fumonisin B1 by rumen microflora. Vet Res Commun 2000;24:379–87.
171. Escoula L. Patulin production by *Pencillium granulatum* and inhibition of rumen flora. J Environ Pathol Toxicol Oncol 1992;11:45–8.
172. Morgavi D, Boudra H, Jouany J, et al. Prevention of patulin toxicity on rumen microbial fermentation by SH-containing reducing agents. J Agric Food Chem 2003;51:6906–10.
173. Logrieco A, Moretti A, Castella G, et al. Beavuericin production by *Fusarium* species. Appl Environ Microbiol 1998;64:3084–8.

174. Xiao H, Marquardt RR, Frohlich AA, et al. Effect of a hay and grain diet on the rate of hydrolysis of ochratoxin A in the rumen of sheep. J Anim Sci 1991;69: 3706–14.
175. Bolsen KK, Huck GL, Siefers MK, et al. Silage management: five key factors. Manhattan (KS): Kansas State University; 1999. Available at: http://www.ksre.ksu.edu/pr_silage/bunker_silo_mgmt.htm. Accessed January 12, 2013.
176. Buening GM, Mann DD, Hook B, et al. The effect of T-2 toxin on the immune bovine system: cellular factors. Vet Immunol Immunopathol 1982;3:411–7.
177. Pier AC. Major biological consequences of aflatoxicosis in animal production. J Anim Sci 1992;70:3964–7.
178. Morris CA, Towers NR, Tempero HJ. Breeding for resistance to facial eczema in dairy cattle. In: Proceedings of the New Zealand Grassland Association. 1991. p. 221–4.
179. Lean IJ. Perennial ryegrass endophytes - effects on dairy cattle. In: Reed KF, Page SW, Lean IJ, editors. Perennial ryegrass toxicosis in Australia. Attwood (Australia): Meat & Livestock Australia; 2005. p. 29–36.
180. Reed KF. Perennial rye grass toxins in Australian pasture. In: Reed KF, Page SW, Lean IJ, editors. Perennial ryegrass toxicosis in Australia. Attwood (Australia): Meat & Livestock Australia; 2005. p. 11–9.