Feeding Cows to Nourish the Dam and the Calf

Alex Bach, PhD
Department of Ruminant Production
IRTA, Barcelona, Spain

Take-Home Message

Past and current nutritional models used to assess nutrient requirements of dairy cattle have attempted to address transition cow issues through the ration of the cow during the last 3-4 weeks preceding parturition and have focused on maximizing production performance and minimizing metabolic upsets of the lactating cow. The nutritional models used today, though, assume that nutrient requirements for pregnancy are only relevant for the last 3 months of gestation and neglect any potential long-term effect of maternal nutrition on the offspring, in spite of current evidence suggesting that nutrient supply and hormonal signals at specific windows during development (both pre- and early postnatal) may exert permanent changes in the metabolism of the offspring. Since the early 90's (and especially after the release of the NRC model in 2001, which recommends energy densities around 1.60 Mcal of NEl/kg during this period) late pregnant cows have been fed high-energy rations in the immediate pre-calving period to 1) compensate for the assumed decrease feed intake as calving approaches, 2) minimize body fat mobilization, ketosis, and fatty liver after calving, 3) adapting the rumen microflora towards a high nutrient dense ration (that will be fed post-calving), and 4) foster the growth of rumen papillae to minimize the risk of rumen acidosis during lactation through an improved absorption (and removal) of volatile fatty acids from the rumen. However, the proposed high-energy diet before calving does not seem to offer a plausible solution for these issues, and feed a low-energy diet before calving seems more logical and effective, because overfeeding energy decreases intake and predisposes the cow to metabolic problems. Diets providing 1.32 Mcal of NEl/kg before calving seem adequate.

On the other hand, postpartum hypocalcemia is a common affliction that increases the odds of several diseases in dairy cattle. Strategies to minimize hypocalcemia consist of 1) feeding anionic salts, 2) feeding low calcium diets.

Most of gestation, especially the first two-thirds, in the lactating cow coincides with lactation, and embryonic development must compete for nutrients against the demands of maternal milk production. There is accumulating evidence that there exist a programming effect of the uterine environment on the future performance of the offspring. Cows born to mothers that were lactating while pregnant (adults cows) produced less milk, had shorter lives, and were metabolically less efficient than cows born to dams that were not lactating while pregnant. This is mainly due to inadequate nutrient supply to the fetus, both in terms of energy and protein, but also micronutrients such as vitamins and amino acids. For example, arginine, leucine, and glucose are essential for the correct development of the histotroph (Kim et al., 2011). Also, vitamin A is important in regulating early lung development and alveolar formation, and thus maternal vitamin A status is important determinant of embryonic alveolar formation and respiratory health. Also, it seems likely that maternal shortages or methyl-donors (folic acid, methionine, vitamin B_{12}) may alter gene expression of the offspring.

It can be expected that in the near future, the pregnant cow will be supplemented with specific amounts of nutrients to ensure optimal fetal development.

Introduction

About 30 to 50% of dairy cows are affected by some form of metabolic or infectious disease around the time of calving (LeBlanc, 2010). In addition, virtually all early-lactation cows experience a period of reduced immune function for 1 to 2 weeks before, and 2 to 3 weeks after calving due to low feed intake, negative energy balance, lipolysis, insulin resistance, and weight loss. Additionally, some may suffer hypocalcemia, uterine infections, ketosis, and displaced abomasum. Past and current nutritional models used to assess nutrient requirements of dairy cattle have attempted to ameliorate these threads through the ration of the cow during the last 3-4 weeks preceding parturition and have focused on maximizing production performance and minimizing metabolic upsets of the lactating cow. These models omit one important aspect: with the exception of copper, nutrient requirements for pregnancy are only considered during the last 3 months of gestation (from 190 to 280 d of pregnancy). The main reason for this is that fetal weight increases exponentially during gestation (House and Bell, 1993) and only the last third is considered to be sufficiently large to start accounting for fetal needs. Fetal sex does not influence growth rates (Ferrell et al., 1982; House and Bell, 1993) although; recent evidence suggests that fetal sex has an impact on the lactogenic capacity of the dam. For instance, Hinde et al. (2014) have reported that heifers that delivered a female calf produce about 450 kg more milk over the first two lactations than those heifers that deliver a male calf.

On the other hand, nutrient supply and hormonal signals at specific windows during development (both pre- and early postnatal) may exert permanent changes in the metabolism of humans (Fall, 2011), as well as changes in performance, body composition, and metabolic function of the offspring of livestock (Wu et al., 2006) through processes generically referred to as fetal programming and metabolic imprinting. Thus, it is likely that the cow of today, with high milk yield but also reproductive and metabolic challenges, is not only a consequence of genetic selection, but also the result of the way her dam was fed and the way she was fed early after birth (Bach, 2012). Long-term modifications of the metabolic function of the offspring during fetal development can occur through epigenetic changes (Anderson et al., 2006; Wu et al., 2006), which mainly involve modifications in the chromatin structure through acetylation of histones or methylation of DNA, resulting in modulations of gene expression with independence of gene sequence. Potential causes and consequences of fetal programming events in beef (Funston et al., 2010) and dairy (Bach, 2012) cattle have been recently reviewed.

This article reviews the recommended feeding practices for pregnant cows and the potential connections between nutrition of the dam and metabolic function, milk production, reproduction, and susceptibility to disease of the offspring, as well as future milking performance of the dam.

Nourishing the pregnant cow

Since the early 90's (and especially after the release of the NRC model in 2001, which recommends energy densities around 1.60 Mcal of NEl/kg during this period) late pregnant cows have been fed high-energy rations in the immediate pre-calving period to 1) compensate for the assumed decrease feed intake as calving approaches, 2) minimize body fat mobilization, ketosis, and fatty liver after calving, 3) adapting the rumen microflora towards a high nutrient dense ration (that will be fed post-calving), and 4) foster the growth of rumen papillae to minimize the risk of rumen acidosis during lactation through an improved absorption (and removal) of volatile fatty acids from the rumen.

The first two objectives (compensate reduction of feed intake and minimize body fat mobilization) do not seem to be attained by feeding high-energy diets before calving. Several studies have shown that high-energy density diets fed prepartum do not physically limit intake of

cows (VandeHaar et al., 1999; Mashek and Beede, 2000; Rabelo et al., 2003) resulting in over-consumption of energy. Overconsumption of energy prepartum has been linked to decreases in feed intake prepartum compared with cows that are fed to meet their energy requirements (Agenäs et al., 2003; Dann et al., 2006; Douglas et al., 2006; Guo et al., 2007). Furthermore, Janovick et al. (2011) described that a bulky diet with a low energy density fed prepartum improved metabolic status postpartum, and reduced the incidence of health problems. Interestingly, overfeeding energy to cows during the last 21 days before parturition triggered a robust upregulation of lipogenic gene expression in adipose tissue (Ji et al., 2012), suggesting that insulin sensitivity may not be impaired by the hyperinsulinemic response to overfeeding energy (Janovick et al., 2011; Ji et al., 2012). This situation may increase the odds for cows to accumulate fat pre-calving when feed high-energy density diets. In fact, Drackley et al. (2014) have recently shown that overfeeding energy to nonpregnant-nonlactating cows drastically increases omental, mesenteric, and perirenal adipose tissue of dairy cows, without translating in detectable changes in body condition of the animals. Furthermore, Graugnard (2013) reported that cows that were moderately over-fed during the prepartum period have an altered immune response and more prone to sustain liver lipidosis than those fed low energy diets. Recent evidence (Huang et al., 2014) supports feeding low energy diets (~1.30 Mcal of NEl/kg) prepartum as they result in increased dry matter intake postpartum, milk yield, and alleviate negative energy balance. Thus, the current view is that recommended high-energy feeding during the dry period, especially as calving approaches, may be detrimental to cow health, or at least unnecessary, as a much lower energy density is sufficient to meet the energy requirements of the late pregnant cow. An average pre-partum cow requires about 15 Mcal of NEl/d, and feeding a ration with an energy density of 1.60 Mcal of NEl/kg ration would readily provide more than 19 Mcal of NEl/d. Consequently, lower energy rations (approx. 1.32 Mcal/kg of NEl) should be sufficient to meet the energy requirements of dry cows. Cereal straw provides an excellent source of fiber in such rations as well as an important energy diluent provided the ration is well mixed to avoid ingredient selection by the cows. With respect to dietary protein, feeding rations of approximately 13% crude protein are recommended, possibly marginally greater when a significant numbers of first-calving heifers are being fed.

The third objective (adapting the rumen microflora to a high-starch diet) is also debatable. In ruminant nutrition it has typically be assumed that at least 3 week are needed for the rumen microflora to adapt to a dietary change. However, the vast majority of organisms in the rumen are bacteria and they can double their population in as fast as 20 min. Thus, 3 weeks seems like an extremely long time to consolidate a change in term of bacteria lifespan. In fact, Fernando et al. (2014) have recently evaluated changes in the rumen microbial population when shifting steers from a prairie-based diet to a high-grain ration. Within a week of each step-up (animals were gradually moved to a high-grain diet), the authors already reported drastic changes in the rumen microbial population.

Lastly, the fourth objective (fostering growth of rumen papillae) could also be argued. The NRC (2001) made this recommendation based on the study by Diksen et al. (1985) that compared the characteristics of rumen papillae between cows fed a straw-based gestation ration to a high concentrate lactation ration. However, studies substituting barley for forage in the diets of late-gestation dairy cows, in an attempt to increasing rumen acid load and alter rumen volatile fatty acid concentrations, had no effect on rumen papillae characteristics (Andersen et al., 1999) or subsequent lactation performance (Ingvartsen et al., 2001). Furthermore, a more recent study (Reynolds et al., 2004) that compared a high fiber diet vs the same diet plus additional 800 g/d of barley precalving reported that total mass of rumen papillae excised from the floor of the cranial sac was not affected by transition diets, but the number tended to be greater when barley was fed, and this was associated with a marked reduction in average width, which

resulted in a reduced average surface area. Thus, it would seem that there would be no need to 'adapt' rumen papillae before calving by providing high-starch diets.

There are, however, other reasons for feeding special diets pre-calving. These reasons include minimizing the incidence of hypocalcemia and udder edema. Dairy cows have between 2 and 4 g of calcium in blood, half of which is in the ionized form. On the first day of lactation, synthesis and secretion of colostrum impose major losses of calcium equivalent to 7 to 10 times the amount of calcium present in blood (Horst et al., 2005). The incidence of clinical hypocalcemia postpartum ranges between 3.5% in the USA and Australia and 6% in Europe (DeGaris and Lean, 2008); but the thread for dairy cattle lies in the subclinical cases, which have been estimated to about 50% (Goff, 2008). Cows with milk fever are at increased risk of developing other periparturient problems, including dystocia and ketosis (Curtis et al., 1983), displaced abomasum (Massey et al., 1993), uterine prolapse (Risco et al., 1984), and retained placenta (Melendez et al., 2004). Furthermore, hypocalcemic cows have increased plasma concentrations of cortisol (Horst and Jorgensen, 1982), reduced proportion of neutrophils with phagocytic activity (Ducusin et al., 2003; Martinez et al., 2012), and impaired mononuclear cell response to an antigen-activating stimulus (Kimura et al., 2006). This reduction of immune response has linked hypocalcemia to metritis (Martinez et al., 2012) and mastitis (Curtis et al., 1983). Thus, preventing or minimizing the incidence of hypocalcemia should be a priority when feeding prepartum dairy cattle. Strategies to minimize hypocalcemia consist of 1) feeding anionic salts, 2) feeding low calcium diets.

Dry cow diets that are high in potassium, sodium, or both alkalinize the cow's blood and increase the susceptibility for milk fever (NRC, 2001). For many years, it has been known (Ender et al., 1971; Ender and Dishington, 1967; Block, 1984) that addition of dietary anions before calving could prevent hypocalcemia. An acidic diet ameliorates parturient hypocalcemia by enhancing calcium mobilization before parturition by increasing calcium absorption and bone resorption (Damir et al., 1994). When supplementing pre-calving rations with anions, urine pH should be monitored. In Holstein cows, effective anion addition should reduce urine pH to 6.8 (Oetzel and Goff, 1998). The second strategy to minimize hypocalcemia, as stated above, consists on limiting the amount of dietary calcium pre-calving to force the cow to initiate calcium mobilization mechanisms well before parturition. Diets providing less than 15 g/d of calcium and fed for at least 10 days before calving reduce the incidence of hypocalcemia (Boda, 1954; Goings et al., 1974).

Nourishing the calf

Most of gestation, especially the first two-thirds, in the lactating cow coincides with lactation, and embryonic development must compete for nutrients against the demands of maternal milk production (Bell and Bauman, 1997). Nutrition is among the most influential intrauterine factors dictating placental and fetal growth (Barker and Clark, 1997). In dairy cattle, there is little information about the potential effects of maternal metabolic status on subsequent metabolic function of the offspring, and nutrient requirements associated with early pregnancy are ignored and unknown (NRC, 2001). However, embryonic metabolic activity is high and it is a critical period for organogenesis and tissue hyperplasia (Robinson et al., 1999) and fetal development is most vulnerable to maternal nutrition around the peri-implantation period and during rapid placental development (Waterland and Jirtle, 2004).

Several studies have reported clear effects of under-nutrition during pregnancy on birth weight (Tudor, 1972; Micke et al., 2010). In addition to obvious effects on birth weight, maternal (and fetal) nutrition can have long-term metabolic consequences that might be less obvious to identify. For example, Dabelea et al. (2000) illustrated the importance of fetal metabolic

environment on future metabolic function of the offspring when, in a study involving Pima Indians (a population with a great incidence of type II diabetes), they reported that siblings born to mothers that had diabetes had twice as much risk of having type II diabetes than those that were born before the mother had type II diabetes. Thus, the fetal environment clearly programmed the metabolism of the offspring and its consequences were seen later in life, not at birth. Whether this phenomenon occurs in dairy cattle is not well known. Banos et al. (2007) reported no significant effects of maternal milk production during pregnancy on subsequent offspring milking performance in the first lactation, but Berry et al. (2008) found a negative relationship between milk production of the dam and milking performance of the offspring in the first and third, but not second, lactations and concluded that the majority of the maternal effects in progeny performance were due to factors other than maternal milk production. The lack of an association between milk production and long-term effects on the offspring is most likely due to the fact that different milk production levels can occur with distinct metabolic environments in the dam (i.e., negative, neutral, or even positive nutrient balances), and thus, it seems clear that it is the latter, not milk yield *per se*, that may exert modifications in the metabolic function of the offspring. A more recent study (González-Recio et al., 2012) actually reported that cows born to mothers that were lactating while pregnant (adults cows) produced less milk, had shorter lives, and were metabolically less efficient than cows born to dams that were not lactating while pregnant (heifers). Also, Maillo et al. (2012) concluded that the reproductive tract of the lactating dairy cow is compromised in its ability to support early embryo development compared with that of matched dry cows and this may contribute to early embryo mortality observed in such animals.

The energy balance of the dam during gestation seems to exert programming effects on the offspring. In beef cattle, undernutrition of ~75% of recommended allowance during early stages of pregnancy has been shown to compromise placental angiogenesis, cotyledon weight, and fetal development (Vonnahme et al., 2007; Long et al., 2009). Increased adiposity of the fetus seems to be among the potential negative outcomes of an inadequate placental development in sheep (Bispham et al., 2003; Ford et al., 2007). Interestingly, offspring from ewes that were overfed throughout gestation did not show differences in growth until 19 months of age (Long et al., 2010). At that age, when lambs were exposed to ad libitum feeding, offspring from overfed ewes had consistently greater plasma leptin concentrations, but similar intakes (which indicates a state of leptin resistance) than control animals. On the other hand, Osorio et al. (2013) provided evidence, in dairy cattle, for a carry-over effect of maternal energy overfeeding during the last 3 weeks before calving on some measurements of metabolism in the calf at birth and the phagocytic capacity of blood neutrophils after colostrum feeding. Similarly, maternal overfeeding in sheep has been associated with type 2 diabetes, hypertension, and fetal growth retardation in the offspring (Wallace et al., 1999; Wang et al., 2010). These studies would, then, support, feeding a low-energy diet before calving.

On the other hand, a protein deficiency (i.e., 65% of recommendations) may compromise the reproductive performance of the offspring. For instance, in primiparous beef cows during the last 100 days of pregnancy delayed age at puberty of the progeny (Corah et al., 1975), whereas heifers born to dams supplemented with protein during the last third of pregnancy had increased pregnancy rates compared with heifers born to nonsupplemented dams (Martin et al., 2007). Furthermore, protein deficiencies at the end of the gestation seem to alter the hormonal content of the colostrum and this, in turn, may compromise intestinal maturation and the immune passive transfer of the calf. Linear decreases in protein intake during the last 100 d of gestation resulted in linearly impaired serum IgG concentrations in the calf, despite the fact that IgG concentration in the colostrum and amount of colostrum consumed by calves was not affected (Blecha et al., 1981). Meyer et al. (2010) illustrated that a moderate (i.e., ~80% of recommendations) nutrient restriction during early to mid-pregnancy of beef cattle altered the

jejunal proliferation and total intestinal vascularity of the fetus, which could alter the capacity for IgG absorption.

Although macro nutrient requirements (energy, protein, etc.) for embryonic growth are low in early pregnancy, it is likely that the embryo is sensitive to deficiencies of micronutrients such as specific amino acids, vitamins, etc.... as well circulating concentrations of hormones and growth factors. For example, arginine, leucine, and glucose are essential for the correct development of the histotroph (Kim et al., 2011). Also, vitamin A is important in regulating early lung development and alveolar formation, and thus maternal vitamin A status is important determinant of embryonic alveolar formation and respiratory health. Checkley et al. (2010) have recently reported, in humans, that vitamin A supplementation of deficient pregnant mothers greatly improved the respiratory health of the offspring.

In swine, arginine supplementation during pregnancy increased live litter weight by 24% (Mateo et al., 2007). However, the potential effects of arginine supplementation on placental vascularization and adiposity of the bovine fetus are unknown. The only study that have assess the effects of arginine on placental development in dairy was conducted by Yunta et al. (2013), who described that arginine supplementation form 40 to 146 d of pregnancy in heifers decreased maternal concentrations of the remaining essential amino acids in blood and, contrary to initial expectations, decreased blood flow volume to the placenta. On the other hand, the fetus seems to rely heavily on branched-chain amino acids, especially leucine and valine, plus methionine (Van den Akker et al., 2011).

Methionine has been identified as a limiting amino acid in both lactating (Schwab et al., 1992; Bach et al., 2000a) and dry cows (Wray-Cahen et al., 1997; Bach et al., 2000b). Methionine has been reported to be transported into bovine embryonic cells (Gopichandran and Leese, 2003) and to participate in the regulation of translation and DNA methylation (Métayer et al., 2008). Thus, perturbations in the methionine-homocysteine and folate cycles, associated with inadequate methionine supply during development stages, may lead to hypomethylation of DNA and dysregulation of gene expression and metabolism of the offspring (Petrie et al., 2002). Sinclair et al. (2007) reported evident changes in the methylation status of lambs born to mothers with a restricted supply of methyl donors (i.e., vitamin B_{12}, folate, and methionine) compared with those born to ewes under physiological ranges. Vitamin B_{12} is a water-soluble vitamin produced by rumen microbes for their use and use by the host animal. In early lactation, dairy cattle fed supplementary folic acid and rumen-protected methionine were observed to have lower-than-optimal levels of vitamin B_{12}, confirmed by reduced serum methylmalonic acid concentrations and increased milk production of primiparous cows given weekly intramuscular vitamin B_{12} injections (Girard and Matte, 2005); thus, it could be hypothesized that the fetus of cows that become pregnant in early lactation may experience some shortages of vitamin B_{12}, and thus, potentially, a shortage of methyl donors and some dysregulation in gene expression. IN fact, in humans, a clear correlation between vitamin B_{12} status and the degree of methylation of the offspring has been recently documented (McKay et al., 2012). Furthermore, reduced methylation of several genes in cord blood DNA has been associated with increased folic acid intake during pregnancy (Hoyo et al., 2011) and genome-wide DNA methylation in cord blood DNA correlated inversely with maternal plasma homocysteine concentration (Fryer et al., 2009).

Lastly, not only the nutritional environment may program or alter the metabolism of the offspring. For instance, Tao and Dahl (2013) reported that heat stress in late gestation decreases birth weight of newborn farm animals, which reflects compromised fetal development in utero. Interestingly, fetal growth retardation under heat stress is independent of the nutritional status of the dam (Brown et al., 1977). Furthermore, Tao et al. (2012) described that heat stress of the dam during the dry period compromises immune function of offspring from birth through

weaning. Across many species under thermoneutral conditions, the fetus has a consistently higher body temperature relative to its dam (Laburn et al., 2000; Asakura, 2004), which is mainly due to poor heat exchange with the dam and about a 2-fold greater metabolic rate of the fetus relative to that of the dam (Schröder and Power, 1997; Laburn et al., 2000; Asakura, 2004). Interestingly, calves born to heat-stressed dams have greater insulin concentrations (which may suggest a state of insulin resistance) relative to calves born to cooled dams when consuming the same amounts of colostrum the first 4 days after birth (Nardone et al., 1997).

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