**ABSTRACT**

Energy intake and partitioning are determined by many interacting factors and their prediction is the Achilles’ heel of ration formulation. Inadequate energy intake can limit milk yield and reproductive performance, whereas excessive energy intake will increase body condition, increasing the risk of health and reproductive issues in the subsequent lactation. Ration composition interacts with the physiological state of cows, making it difficult to predict DMI and the partitioning of energy accurately. However, understanding the factors controlling these allows us to devise grouping strategies and manipulate rations to optimize energy intake through lactation. Eating is controlled by the integration of signals in brain feeding centers. Ration composition affects DMI of cows via signals from ruminal distention and the hepatic oxidation of fuels. Dairy cow rations must contain a minimal concentration of relatively low-energy roughages for proper rumen function, but signals from ruminal distention can limit DMI when the drive to eat is high. Signals from the hepatic oxidation of fuels likely dominate the control of DMI in the peripartum period when cows are in a lipolytic state and later in lactation when signals from distension diminish. Therefore, the effects of the ration on DMI vary with the physiological state of the animal. Furthermore, they interact with environmental stressors such as social (e.g., overcrowding) and thermal stress. The objective of this article is to discuss the effects of ration composition on energy intake and partitioning in lactating cows and how they can be manipulated to optimize productive performance.

**Key words:** hepatic oxidation theory, maintenance group, body condition, feeding strategy

**INTRODUCTION**

Properly balanced rations must consider their effects on energy intake and partitioning to optimize milk production and prevent excessive loss or gain in body condition throughout lactation. However, this is not considered by ration formulation programs that predict DMI by animal factors only (e.g., milk energy output, BW, DIM) or that include loss or gain in BW as user inputs to the program. Ration composition can have large effects on energy intake and partitioning, which vary as physiological state changes throughout lactation (Allen, 2000). Understanding factors affecting energy intake and partitioning permit an improved approach to ration formulation and grouping of lactating cows. This article is 1 of 4 from a symposium on this topic for which my research group has contributed to the understanding over the years. Among these, Oba and Kammes-Main (2023) discuss carbohydrate digestion and limitation of DMI by distension of undigested feed residues in the gastrointestinal tract, Albornoz et al. (2023) focus on the control of DMI by hepatic oxidation of fuels, and Piantoni and VandeHaar (2023) review the effect of absorbed fuels on energy partitioning. The objectives of this article are to (1) integrate our collective knowledge of how rations varying in composition interact with the physiological state to affect energy intake and partitioning by cows as they progress through lactation, and (2) discuss how this knowledge can be used to improve ration formulation. It will address changes in the physiological state throughout lactation, limitations and benefits of the filling effect of rations, effects of ration starch concentration and fermentability, grouping cows by physiological state, and recommendations for ration formulation to improve milk yield and efficiency of nutrient utilization.
Transition Period

This period is characterized by the homeorhetic adaptation to a lipolytic state to prepare for the transition from pregnancy to lactation (Bauman and Currie, 1980). The lipolytic state is initiated by a continuous decline in plasma insulin concentration of 50% or more beginning several weeks before parturition (Doepel et al., 2002), as well as decreased insulin sensitivity of adipose tissue from inflammation (Bradford et al., 2015) and increased plasma concentration of somatotropin (Etherton and Bauman, 1998).

The decline in DMI as parturition approached may begin several days (Huzzey et al., 2007; Pérez-Báez et al., 2019) to more than 2 wk prepartum (Doepel et al., 2002; Gulay et al., 2004). Changes in DMI and plasma nonesterified fatty acid (NEFA) concentration in the peripartum period have been shown to mirror each other (Doepel et al., 2002), so the decline and recovery of DMI might be linked to the change in plasma NEFA concentration (Allen, 2014). Hepatic oxidation of acetyl CoA (AcCoA) likely contributes to the reduction in DMI in the peripartum period as plasma NEFA concentration and uptake by the liver increases (Allen et al., 2009). Euglycemia is maintained through the prepartum period (Doepel et al., 2002) despite the reduction in DMI as tissues use NEFA for energy, sparing glucose. Glucose demand increases dramatically at the initiation of lactation resulting in a sharp decrease in plasma glucose concentration (Doepel et al., 2002). Energy needs of tissues are met primarily by oxidation of circulating NEFA, acetate, and ketone bodies, sparing glucose, whereas propionate, glucogenic AA, lactate, and glycerol are used primarily for gluconeogenesis (Aschenbach et al., 2010). The mammary gland extracts NEFA from the blood and exports it as triglycerides in colostrum and early milk, increasing the energy needed for the survival of the neonate (Allen and Piantoni, 2014). Plasma insulin concentration and sensitivity of tissues to insulin remain low and plasma NEFA concentration remains elevated for several weeks or more postpartum (Vernon, 2005). The elevated plasma NEFA concentration and ketone bodies continue to provide energy to extrahepatic tissues when plasma glucose and insulin concentrations are low.

Early to Mid Lactation

Milk yield increases rapidly following parturition and, over the first several weeks postpartum, plasma glucose concentration and insulin secretion gradually increase, resulting in a reduction of lipolysis and plasma NEFA concentration. Because fewer NEFA are available for oxidation, AcCoA availability in the liver decreases, and its export as ketone bodies is diminished. Reduced AcCoA availability and high glucose demand reduce ATP accumulation in the liver, and satiety signals from the liver to the brain decrease (Allen, 2020). The length of time that NEFA remains elevated varies among cows and depends upon the rate of fat mobilization and removal from the blood by the liver and mammary gland. This change in the dominant mechanism of intake regulation might occur as early as 7 to 10 d after parturition for some cows in the herd or more than 3 wk for others (personal observation). Signs that control of DMI by hepatic oxidation is lessened are lower plasma NEFA and ketone concentrations, more aggressive feeding, and steadily increasing DMI.

As lactation progresses over the weeks following parturition and the lipolytic state wanes, a signal from ruminal distension by undigested feed residues in the rumen begins to dominate the control of DMI. The extent to which the filling effect of the ration limits DMI increases with milk yield (Oba and Allen, 1999a; Voelker et al., 2002). As plasma somatotropin concentration declines past peak lactation, insulin sensitivity of adipose tissue increases along with plasma concentrations of glucose and insulin. Energy balance turns positive, gradually replenishing body condition lost in early lactation.

Late Lactation

As energy requirements decrease following peak milk yield, ruminal distension gradually lessens, and hepatic oxidation begins to dominate control of DMI. Individual cows with an adequate supply of glucogenic precursors will respond to a further increase in supply by partitioning more energy to body reserves as plasma insulin concentration and insulin sensitivity of adipose tissue increase. Rations containing more fermentable starch can depress DMI (Oba and Allen, 2003b; Bradford and
Allen, 2007) and ruminal pH, which can cause milk fat depression by altering biohydrogenation of fatty acids (Bradford and Allen, 2004). The energy spared from the reduction in milk fat synthesis is likely partitioned toward body reserves (Harvatine et al., 2009).

The importance of controlling body condition at calving is well recognized. Cows with excessive body condition generally mobilize fat very rapidly through the transition period (Garnsworthy and Topps, 1982) because their tissues are more insulin resistant and they have greater fat stores to mobilize. Therefore, it is very important to limit the prevalence of over-conditioned cows by reproductive management, grouping lactating cows, and appropriate ration formulation. Rations should be formulated to provide adequate nutrients to maintain or enhance milk yield while maintaining body condition until dry-off. Allowing cows to consume more energy than required during the dry period results in increased NEFA concentrations in early lactation (Holtenius et al., 2003).

**FILLING EFFECT OF RATIONS**

The filling effect of a ration is determined by the initial bulk density of feeds, as well as their filling effect over time in the rumen. Forage NDF is less dense initially, digests more slowly, and is retained in the rumen longer than other ration components (Allen, 2000). The overall filling effect is determined primarily by forage NDF concentration, forage particle size, the fragility of forage NDF determined by forage type (legumes, perennial grasses, annual grasses), and NDF digestibility within a forage type (Allen, 2000).

**Benefits of Rumen Fill**

Whereas ruminal distension becomes a primary limitation to DMI as milk yield increases, it likely has less effect on DMI during the transition period when DMI is controlled by hepatic oxidation. Rations can be formulated to meet requirements with large differences in the amount and turnover rate of ruminal digesta (Allen, 1996). Formulating rations to maintain rumen fill with ingredients that are retained in the rumen longer, have moderate rates of fermentation, and have high ruminal digestibility will likely benefit transition cows in several ways. The ruminal digesta will provide more energy over time when DMI decreases at parturition, or from metabolic disorders or infectious diseases (Allen and Piantoni, 2013). This will help maintain plasma glucose concentration and reduce the rapid mobilization of body reserves compared with when rations are formulated with ingredients that clear from the rumen quickly. Ruminal digesta is very important to buffer fermentation acids and buffering capacity is directly related to the amount of digesta in the rumen (Allen, 1997). Therefore, rations formulated with ingredients that increase the amount of digesta in the rumen will have greater buffering capacity and will maintain buffer capacity longer if DMI decreases. Inadequate buffering can result in low ruminal pH, decreasing fiber digestibility and acetate production, and increasing propionate production, possibly decreasing DMI by stimulating oxidation in the liver. Low ruminal pH also increases the risk of health problems such as ruminal ulcers, liver abscesses, and laminitis, and causes inflammation, likely increasing mobilization of body reserves even further. Rations formulated with ingredients that maintain digesta in the rumen longer when DMI decreases will likely also decrease the risk of abomasal displacement.

**Limitations on Feed Intake**

Following the fresh period, high-producing dairy cows should be offered a less filling ration to maximize DMI. Dry matter intake of lactating cows is often dramatically reduced by increasing the forage NDF concentration of the ration. Several studies in the literature reported a decrease in DMI of up to 4 kg/d when ration NDF concentration was increased from 25 to 35% by substituting forages for concentrates (Allen, 2000). Although most studies reported a significant decrease in DMI as forage NDF increased, the responses in DMI have been variable, depending upon the degree to which intake was limited by distension and the forage source. Dry matter intake of higher producing cows is limited by distension to a greater extent (Oba and Allen, 1999a,b; Voelker et al., 2002) and the filling effect of forage fiber varies greatly (Allen, 1996; Oba and Kammes-Main, 2023).

Characteristics related to the filling effect of rations have been used to predict the DMI of lactating cows past 60 d postpartum (Allen et al., 2019). An equation was developed using treatment means reported in the literature and included milk yield as well as ration forage NDF concentration, in vitro or in situ digestibility of forage NDF, and the ratio of ADF to NDF in the ration. The ratio of ADF to NDF was used to help differentiate differences in forage fragility across forage families (grass vs. legume). Forage NDF digestibility interacted with both the ratio of ADF to NDF in the ration as well as milk yield. Dry matter intake increased with increasing forage NDF digestibility for higher producing cows but decreased for lower producing cows. The predicted mean DMI was 23.0 kg/d with no mean bias, a root mean square error of 1.55 kg/d, and a concordance correlation coefficient of 0.83 (Allen, 2000).
et al., 2019). The equation should help predict DMI response to the filling effects of rations during ration formulation (NASEM, 2021).

**CONTROL OF FEED INTAKE BY HEPATIC OXIDATION**

Previous reviews have focused on different aspects of the hepatic oxidation theory of the control of DMI (Allen et al., 2009; Allen, 2014, 2020; Alborno et al., 2023), and the control of DMI by hepatic oxidation will be discussed herein as it relates to ration formulation. Hepatic oxidation of fuels in the tricarboxylic acid (TCA) cycle is determined by the availability of AcCoA for the citrate synthase reaction and flux through the TCA cycle, affected by the balance between anaplerosis and cataplerosis and activity of TCA cycle enzymes (Allen, 2020). Propionate is the primary anaplerotic metabolite stimulating oxidation during the timeframe of meals (Allen, 2020) and the hypophagic effects of propionate were related linearly with hepatic concentration of AcCoA for cows in the postpartum period (Stocks and Allen, 2012). Because it can stimulate hepatic oxidation, it is more hypophagic than acetate (Oba and Allen, 2003a) as well as glycerol (Gualdrón-Duarte and Allen, 2017), which can enter the gluconeogenic pathway in the cytosol without stimulating oxidation. Propionate decreased ME intake compared with isoenergetic infusion of glucose and reduced DMI compared with isoenergetic infusion of lactic acid when infused into the abomasum (Gualdrón-Duarte and Allen, 2018). The extent to which hepatic oxidation contributes to the control of DMI depends upon other mechanisms limiting DMI (e.g., rumen distension). It is important to note that mechanisms controlling DMI are not mutually exclusive and dominant mechanisms vary both within and across days (Allen, 2020).

*Flux Through AcCoA*

Hepatic oxidation of NEFA is a 2-stage process; specifically, long carbon chains of fatty acids are partially oxidized to AcCoA, a 2-carbon molecule, which is then either completely oxidized in the TCA cycle or exported as ketone bodies (e.g., BHB, acetoacetate) or acetate. The ability of the liver to completely oxidize NEFA is limited, so ketone bodies are exported and their concentration in plasma is elevated when fat mobilization is high. Export of ketone bodies from the liver is desirable because it decreases AcCoA available for oxidation in the liver, potentially increasing DMI, and ketone bodies are used by tissues for energy, sparing glucose. However, metabolic disturbances from keto-acidosis can result when their production greatly exceeds their utilization by tissues, increasing their concentration in plasma. Availability of AcCoA in the liver varies through lactation; hepatic concentration of AcCoA is greater in early lactation when plasma NEFA concentration is elevated and less in later lactation when plasma NEFA concentration is diminished (Piantoni et al., 2015b).

*If Hepatic Oxidation of NEFA Suppresses DMI, Why Do Cows in a Lipolytic State (e.g., Starved, Postpartum) Eat at All When the Liver Is Awash in NEFA?* Cows initiate meals when the liver energy status is low and terminate meals when it is elevated (Allen et al., 2009). The energy produced by hepatic oxidation is continuously used for gluconeogenesis and other metabolic processes. At the initiation of meals, hepatic energy status is low because the supply of anaplerotic metabolites has diminished since the previous meal, and the utilization of ATP has exceeded its production. Greater anaplerosis during meals increases hepatic oxidation of AcCoA and the production of reducing equivalents. However, ATP production from reducing equivalents by oxidative phosphorylation is stimulated by bicarbonate ions (Acrin-Perez et al., 2009) produced primarily in the during oxidation in the TCA cycle. This potentially results in a lag, delaying the increase in hepatic energy status (Allen and Piantoni 2013). In addition, the increase in hepatic energy status can be slowed by metabolic bottlenecks in the TCA cycle (Kennedy and Allen, 2019; Maldini et al., 2019), delaying the satiety signal.

The length of meals is likely affected by the supply of AcCoA from β-oxidation of NEFA in the liver. Insulin release during meals interrupts the supply of NEFA to the liver by inhibiting lipolysis. Plasma concentrations of NEFA and insulin vary inversely as they fluctuate during the course of a day when plasma insulin concentration increases within meals and decreases following meals (Allen et al., 2005). Plasma NEFA concentration is greatest before feeding and reaches a daily nadir several hours after feeding for cows fed ad libitum once per day in the morning (Allen et al., 2005). The pool size of AcCoA varies greatly during the course of a day depending upon the plasma concentration and hepatic uptake of NEFA (Piantoni et al., 2015b). Continuous intraruminal infusions of propionic acid reduced DMI only for the first 4 h after feeding each day when plasma NEFA concentrations were elevated, with no effect over the remaining 20 h when plasma NEFA concentrations were lower (Stocks and Allen, 2013). In addition, cows with greater insulin response to a glucose challenge were better able to maintain DMI when offered a more fermentable ration (Bradford and Allen 2007).

*The Supply of AcCoA to the Liver Is Affected by Insulin Sensitivity of Adipose Tissue.* Dry
matter intake by cows in the postpartum period over the first 4 h following feeding was related positively to the reduction in plasma NEFA and hepatic AcCoA concentrations following feeding (Piantoni et al., 2015b). Dry matter intake among cows ranged from 3.7 to 9.6 kg/4 h which was likely because of differences in insulin sensitivity of adipose tissue. This is because DMI was not related to plasma concentrations of insulin or NEFA before feeding or the change in plasma insulin concentration over the 4-h period. Therefore, although the depression in DMI postpartum is related to the lipolytic state and the availability of NEFA and AcCoA for hepatic oxidation, it is likely not directly related to the mean plasma NEFA concentration throughout the day. The hypophagic effects of elevated plasma NEFA concentrations in the postpartum period vary among cows, depending upon the extent to which lipolysis is interrupted during meals affecting the supply of NEFA to the liver. The interruption of lipolysis is dependent upon the insulin sensitivity of adipose tissue in response to insulin released during meals. The reduction of insulin sensitivity of adipose tissue in response to endotoxins (Chirivi et al., 2022) possibly contributes to the hypophagia from diseases common in the peripartum period (e.g., mastitis, metritis, pneumonia) by reducing the anti-lipolytic effects of insulin. Efforts to increase insulin sensitivity of adipose tissue will likely increase the anti-lipolytic effects of insulin. This is because DMI and reduce negative energy balance during the postpartum period (e.g., mastitis, metritis, pneumonia) by reducing hypophagia from diseases common in the peripartum period (e.g., mastitis, metritis, pneumonia).

Feeding behavior is affected by the amount and temporal pattern of propionate absorbed into the blood. More fermentable high-moisture corn decreased DMI compared with dry ground corn by decreasing meal size (Oba and Allen, 2003b). The more fermentable high-moisture corn likely had a faster production and absorption of propionate as well as more total propionate produced. Faster production and absorption of propionate might stimulate oxidation faster, reducing meal size. However, it could also result in increased meal size (Maldini and Allen, 2018) by stimulating insulin release, thereby decreasing plasma NEFA concentration and availability of AcCoA for oxidation, or by a bottleneck in the TCA cycle (Maldini et al., 2019; Kennedy and Allen, 2019). Whereas feeding behavior (meal size and frequency) was affected by infusion of the same amount of propionate at different rates, there was no effect on DMI (Maldini and Allen, 2018), suggesting that feeding frequency can compensate for differences in meal size under some conditions and that effects of propionate on DMI are affected primarily by the amount of propionate produced over timeframes longer than the length of meals. Whereas propionate is the primary anaplerotic nutrient stimulating hepatic oxidation within the timeframe of meals, other glucogenic nutrients (e.g., AA, glycerol, and lactate) likely stimulate hepatic oxidation following meals and affect the time between meals and meal frequency (Allen, 2020).

Oxidation in the TCA Cycle

The rate at which AcCoA is oxidized in the TCA cycle is a function of the balance between anaplerosis and cataplerosis of metabolites and the activity of TCA enzymes. The glucogenic capacity of the liver is increased by glucose demand as limiting enzymes in the liver are upregulated to meet demand, increasing cataplerosis of the TCA cycle. Because of this, the number of spins of the TCA cycle by each anaplerotic molecule is less, reducing its hypophagic effect compared with late lactation when glucose demand is lower and plasma insulin concentration is higher. When cows are in positive energy balance, plasma insulin concentration is increased and gluconeogenesis is downregulated, decreasing cataplerosis, and increasing the concentrations of TCA intermediates and TCA capacity for oxidation. Consistent with this, the depression of DMI by a ration containing a more fermentable starch source was correlated positively (r = 0.53, P < 0.01) with plasma insulin concentrations among cows past peak lactation (Bradford and Allen, 2007).

ALTERING RATION STARCH CONCENTRATION AND FERMENTABILITY

Starch Concentration

Starch concentration in rations is often reduced by substituting forage or non-forage fiber sources (NFFS) such as beet pulp or soyhulls for cereal grains (Allen and Piantoni, 2014). Dilution of starch in the ration by adding forage or NFFS has the added benefit of reducing the fermentation rate of starch and the rate of propionic acid production (Oba and Allen, 2003b). The optimal strategy depends upon the relative cost of ingredients, efficiency of feed utilization, and animal production response. For instance, longer fiber particles from forage compared with NFFS might increase fiber digestibility by increasing ruminal pH through stimulation of rumination and by increasing ruminal retention and therefore buffering capacity of the rumen digesta. However, distension from the greater filling effect of forage NDF might limit DMI compared with NFFS. Therefore, when ruminal distension contributes to the control of DMI, the substitution of NFFS is a more
suitable alternative than the substitution of forage for cereal grains.

**Starch Fermentability**

Substitution of a less fermentable starch source is an option for cows in the postpartum period or late lactation when the control of DMI is likely dominated by hepatic oxidation. Starch sources with lower ruminal digestibility but with high digestibility in the small intestine will provide the greatest yield of glucose precursors. For instance, dry ground and cracked corn both slow the rate of propionic acid production in the rumen compared with high-moisture corn, but the ground corn will provide more glucose precursors because of greater digestibility in the small intestine.

**Effects on Feed Intake and Milk Yield: Postpartum Period**

A challenge in ration formulation for cows in the postpartum period is that greater glucose production is needed to restore euglycemia, but the primary gluconeogenic metabolite, propionate, can suppress DMI. Ration formulation options can help alleviate the depression in DMI, including manipulating propionate production from the ration, supplying other glucose precursors (e.g., glycerol) that result in slower or less anaplerosis (Gauldrón-Duarte and Allen, 2017), and providing alternate energy sources for tissues to spare glucose (acetate from digestible fiber). The goal to attain euglycemia is to maximize the amount of glucose produced or spared per unit of ATP generated in the liver over time (Allen, 2014). Manipulating the temporal pattern of oxidation of fuels in the liver can increase plasma glucose and insulin concentrations, decreasing fat mobilization, and the period in which DMI is suppressed by hepatic oxidation.

Several experiments have fed rations differing in starch concentration in the postpartum period (Andersen et al., 2003; Rabelo et al., 2005; Dann and Nelson, 2011). Increasing ration starch concentration increased DMI and milk yield in experiments reported by Andersen et al. (2003) and Rabelo et al. (2005). In those experiments, grains were substituted for forage, decreasing the forage NDF concentration of the ration. Because forage NDF is very filling (Allen, 2000) the large increases in the forage NDF concentration of rations in these studies likely contributed to satiety by increasing ruminal distension, especially as lactation progressed and the lipolytic state diminished. Dann and Nelson (2011) substituted corn meal for NFFS to increase ration starch concentration from 21 to 25.5% and the higher starch ration decreased DMI by 1.5 kg/d. Non-forage fiber sources are much less filling than forage NDF (Allen, 2000), so the filling effects of the treatment rations were likely much more similar in that experiment than when grains are substituted for forage.

Several experiments have evaluated the effects of ruminal fermentability of starch in rations fed to cows in the postpartum period (Dann et al., 1999; Sadri et al., 2009; Rockwell and Allen, 2016). Increasing ruminal starch fermentability by substituting steam-flaked corn for cracked corn tended to decrease DMI by more than 1 kg/d over the first 63 d postpartum; additionally, interactions with time were not reported and greater ruminal fermentability would be expected to have a greater effect in the first few weeks of lactation (Dann et al., 1999). Sadri et al. (2009) compared grains varying in ruminal starch fermentability through the transition period and the more fermentable barley treatment decreased DMI compared with corn during both the prepartum and postpartum periods. Substitution of high-moisture corn for dry corn did not affect DMI by cows in the postpartum period in another study (Rockwell and Allen, 2016), likely because DMI was limited by distension from the ration with a high (27%) concentration of forage NDF.

Albornoz and Allen (2018) conducted a study to evaluate the combined effects of ration starch concentration (22 vs. 28%) and starch fermentability (high-moisture corn vs. dry corn) on DMI and milk yield of cows in the postpartum period. Ration starch concentration (corn substituted for soyhulls) had no effect on DMI or FCM during the first 23 d postpartum, but the ration with the more fermentable high-moisture corn decreased DMI by 2.4 kg/d and FCM by 4.9 kg/d.

**Effects on Feed Intake and Milk Yield: Post Peak Lactation**

Increasing the starch concentration of the ration (~23 to 34%) at the expense of forage NDF (~24 to 16%) increased DMI of lactating cows linearly with pretrial milk yield (ranging from ~23 to 59 kg/d FCM), likely because rumen distension limited DMI to a greater extent for cows with greater milk yield (Voelker et al., 2002). However, FCM increased only for cows with an initial FCM yield above 45 kg/d. The lack of response in FCM for cows below 45 kg/d FCM was likely from the effects of the diet on digestibility and energy partitioning among cows.

Substitution of a more fermentable starch source for a less fermentable starch source dramatically reduced DMI of cows past peak lactation in several studies but had no effect on DMI in other studies (Allen, 2000). Oba and Allen (2003b) evaluated effects of ration starch concentration (21 vs. 32%) and starch ferment-
ability (high-moisture corn vs. dry ground corn) on the productive performance of cows past peak lactation. The high-starch ration increased solids-corrected milk yield by 3.3 kg/d (35.2 vs. 31.9 kg/d) compared with the low-starch ration for the dry ground corn treatment only. For the high-moisture corn treatment, the high-starch ration reduced milk fat concentration and yield with no effect on solids-corrected milk yield. The effects of starch fermentability on milk fat production were reported to be dependent upon the productivity of cows. Higher starch fermentability caused a depression in milk fat production for lower producing cows but not in more productive cows, which was related to altered biohydrogenation of fatty acids for the lower producing cows (Bradford and Allen, 2004).

**ENERGY PARTITIONING**

Whereas milk production by cows in early lactation responds well to rations with high-starch concentration, cows in late lactation partition excess energy to body condition. Intravenous infusion of glucose up to 30% of net energy requirement linearly increased plasma insulin concentration, energy balance, BW, and back fat thickness, without affecting DMI or milk yield of mid-lactation cows (Al-Trad et al., 2009). Rations can be easily altered to decrease gain in body condition without losing milk yield when cows are in positive energy balance (Piantoni and VandeHaar, 2023). Substitution of digestible fiber for starch greatly alters fuels available for intermediary processes and often reduces energy partitioned to body condition with no change (Ipharraguerre et al., 2002; Voelker and Allen, 2003) or an increase in milk energy output (Mahjoubi et al., 2009).

**GROUPING AND RATION CHARACTERISTICS**

Whereas the change in the physiological state of cows is continuous throughout lactation, it is impractical to feed many different rations. Three different rations that vary in ingredients and nutrient specification are likely sufficient to manage energy intake and partitioning. Cows within groups can be managed individually by moving them to another group (ration) when appropriate. The 3 rations are fresh, early- to mid-lactation, and maintenance.

**Fresh Cow Ration (Parturition to ~10 to 14 Days Postpartum)**

Fresh cows in a lipolytic state are at increased risk for metabolic disorders. These cows require glucose precursors, and rations should contain higher starch concentrations to the extent possible depending upon the starch source. Starch sources with moderate ruminal fermentability and high digestibility in the small intestine such as dry ground corn will provide more glucose precursors by allowing higher starch concentrations and greater DMI. Highly fermentable starch sources such as wheat, barley, low-density steam-flaked corn, high-moisture corn, and corn silage (especially when aged), should be limited to increase DMI and reduce risk of acidosis and displaced abomasum. Length of storage of ensiled corn increases ruminal fermentability of starch as endosperm proteins are solubilized exposing starch granules. Protein solubility and in vitro starch digestibility increased with length of storage up 9 mo (Der Bedrosian et al., 2012; Ferraretto et al., 2015). Supplemen
ting corn silage-based rations with dry ground corn works well with a total starch concentration of up to 28% of DM (Albornoz and Allen, 2018) or possibly more depending upon the fermentability of starch in the corn silage. Relative fermentability of starch in corn silage and high-moisture corn is typically measured by a 7-h in vitro fermentation, but ammonia N and soluble CP are both good indicators of in vitro starch digestibility of corn silage and they may be used to reduce cost of analysis (Ferraretto et al., 2015).

A greater rumen digesta mass is desirable until distention limits DMI; forage NDF increases rumen fill, decreasing the risk of abomasal displacement, and increases acetate production, sparing glucose utilization by extrahepatic tissues. The optimal forage NDF concentration will vary depending upon the length of time cows are fed the fresh cow ration because ruminal distension becomes more limiting as DIM and DMI increase. For instance, when cows were fed a ration with high forage NDF concentration (27.4%), DMI increased over the first ~10 DIM, but then plateaued until 28 DIM, after which DMI increased sharply when switched to a ration with lower (20.4%) forage NDF concentration (Rockwell and Allen, 2016). Piantoni et al. (2015a) fed cows in the postpartum period rations with forage NDF concentrations of 20 and 26% and the higher forage NDF treatment decreased mean DMI 2.8 kg/d compared with the lower forage NDF treatment. In that study, cows were housed in tiestalls and treatments were fed from 1 to 29 d postpartum; therefore, this likely gave an advantage to the ration with lower forage NDF concentration because of the length of time the fresh ration was fed and because slug feeding was reduced for cows in tiestalls. The optimal forage NDF concentration of the fresh cow ration likely ranges from 20 to 23% depending upon the length of time cows remain in the fresh cow group and competition for feed affected by housing type and stocking density. For herds with freestalls in which cows remain in the fresh group
for less than 2 wk, 23% forage NDF is likely optimal, providing benefits with little or no limitation on DMI.

Forages with highly digestible NDF with a relatively long retention time in the rumen (e.g., perennial grasses) are desirable. The use of NFFS should be limited to diluting starch concentration, if necessary. The lipolytic state typically subsides by 10 to 14 d postpartum but can last longer for cows with metabolic disorders. As distension begins to dominate control of DMI, cows should be switched to a less filling ration to increase DMI.

**Early- to Mid-Lactation Ration**

Cows in early to mid lactation have high glucose requirement for milk production and relatively little energy is partitioned to body reserves. Milk production responds well to rations with lower forage NDF concentration with a faster rumen turnover (e.g., alfalfa, brown midrib corn silage). More fermentable starch sources may be fed as DMI is less limited by hepatic oxidation and greater rumen fill increases the capacity to buffer fermentation acids. Starch concentration of rations should be in the range of 22 to 30% (DM basis), although the optimum concentration is dependent upon competition for bunk space (resulting in larger meals from slug feeding), forage/effective NDF concentration, and starch fermentability (NASEM, 2021). Higher starch and lower fill rations generally increase peak milk yield and decrease loss of body condition in early lactation. Once cows replenish body condition lost in early lactation, they should be switched to a maintenance ration with lower concentration and ruminal fermentability of starch.

**Maintenance Ration (Greater than 150 DIM and BCS of 3)**

The maintenance ration is the key component of a ration formulation/grouping system to increase health and production of cows. The goal of the maintenance ration is to maintain ECM yield and body condition through the remainder of lactation. Cows should be offered the maintenance ration when they are regaining BCS and reach a BCS of 3 on a 5-point scale. If they continue to receive a ration with higher starch concentration than needed, BCS will continue to increase, and they will be at increased risk for metabolic disorders following parturition. Cows gain body condition because they are being fed rations with higher starch concentrations than needed for their current requirement for milk production, resulting in increased plasma glucose and insulin concentrations. Lowering ration starch concentration will limit body condition gain while maintaining and possibly improving DMI and yields of milk and milk fat. The optimal concentration of starch is dependent upon the milk yield of the herd, but will likely be in the range of 18 to 22% (DM basis). Starch sources that are highly fermentable (high-moisture corn, bakery waste, aged corn silage, and so on) might reduce DMI and will likely reduce the optimal starch concentration. Dried ground corn is an excellent starch source because it has lower ruminal digestibility (~50–60%) but high total-tract digestibility (>90%). The starch concentration of the maintenance ration should contain adequate, but not excessive, forage NDF concentration for proper rumen function, and NFFS (beet pulp, corn gluten feed, soyhulls, and so on) should be used to dilute starch to the target concentration. Forages with a longer rumen retention time (e.g., perennial grasses) can be used. Once cows enter the maintenance group, BCS gain before parturition should be limited. It is essential to monitor the change in BCS during the maintenance and dry periods and BCS should be recorded for individual cows once they begin receiving the maintenance ration (at BCS of 3.0), at dry-off, and at parturition to help adjust the starch concentration of the maintenance and dry cow rations over time.

**CONCLUSIONS**

Consideration of physiological changes occurring through lactation and the physical and digestion characteristics of feeds beyond their nutrient composition is required to optimize DMI and body condition for lactating cows. Understanding the control of DMI is critical to ration formulation, and the hepatic oxidation theory can contribute to our ability to formulate rations. Whereas further research is needed to better understand animal response to diets, the theory and concepts presented herein will help to formulate rations to improve animal health and productivity.

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