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Nutrition and feeding of dairy cattle

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Introduction

The high producing dairy cow requires a diet that supplies the nutrient needs for high milk production. Carbohydrates, amino acids, fatty acids, minerals, vitamins, and water are all nutrients required by the lactating dairy cow to meet the demand by the mammary gland to produce milk and milk components. However, in order to develop the cow that will produce a high milk yield, it begins with the nutrition of the calf and heifer.

Dairy calf and heifer nutrition and development

Why are dairy calves needed?

Dairy producers raise dairy calves to replace dairy cows that are culled (removed) from the herd for various reasons such as mastitis (infection of the udder), inability to get the cow pregnant (poor reproduction), for feet and leg problems (poor mobility), and for low milk production. An additional reason for the removal of cows from the herd is selling cows

to other dairy producers. Dairy producers planning to increase herd size often increase cow numbers by retaining larger numbers of heifers within the herd. This is referred to as internal herd growth.

Raising heifers constitutes 15%–20% of dairy farm expenses¹ and often is the second or third greatest cost on the dairy farm. Feed cost is the greatest expense while labor is the second or third greatest expense. It is estimated that the cost of raising a heifer from birth to calving is approximately \$2,300 in the Northeastern US. Therefore, the goal is to raise healthy heifers with optimum growth, and reduced veterinary expenses. The optimal age of calving has been established to be between 22 and 24 months of age.^{2,3} Raising healthy calves begins with colostrum.

Colostrum

Colostrum is the first mammary secretion produced by the mammary gland of mammals. It is especially important in pre-ruminant animals like calves. In the uterus (in utero), calves are being nurtured through a six-layered

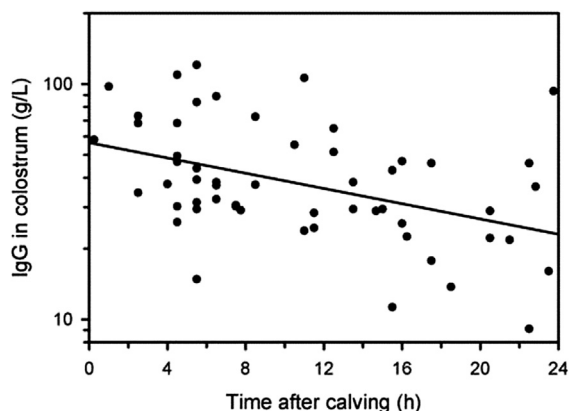


FIG. 9.1 Colostrum quality diminishes as harvest time after calving increases.⁴

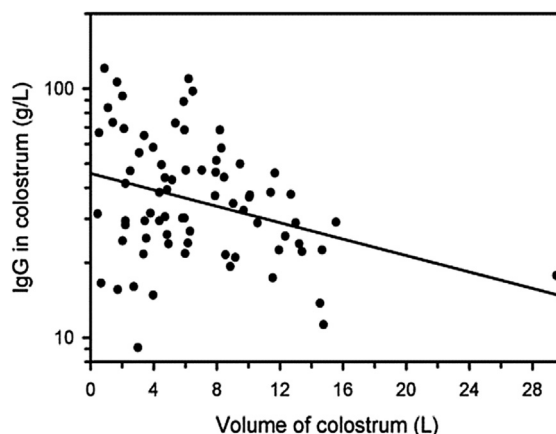


FIG. 9.2 Colostrum quality diminishes as volume increases.⁴

cotyledonary placenta, however, negligible amounts of antibodies (immunoglobulins) get transferred to the fetus during gestation. Therefore, immunoglobulins (Ig) must be provided through the colostrum soon after the calf is born. Immunoglobulins are important in the health of the calf as they provide for the defense against various pathogens and viruses.

Colostrum should be harvested from the cow as soon as possible after calving for several reasons:

- (1) Colostrum quality diminishes over time as the mammary gland changes from colostrum production (colostrogenesis) to milk synthesis (lactogenesis) Fig. 9.1.⁴
- (2) As colostrum volume increases, IgG decreases (Fig. 9.2).⁴
- (3) Absorption of immunoglobulins by the calf is reduced as time after calving increases.

Colostrum quality and feeding

Colostrum quality is determined through the measure of IgG. This is because the IgG is the most important antibody for conveying protection to the calf. The quality of colostrum can be measured through the use of a hydrometer specific for colostrum (also known as a colostrometer)

or with a refractometer. Using a colostrometer requires that the colostrum must be at room temperature otherwise over- or underestimation of the IgG in the colostrum is possible. Good quality colostrum is when the IgG concentration is ≥ 50 g/L. Using a refractometer only requires two drops of colostrum and it does not need to be at room temperature. High-quality colostrum has a refractometer reading of approximately 25% Brix. Brix is a measurement of the sugar content but in colostrum, it measures the total solids content which correlates positively to the IgG concentration in colostrum. Four liters of good quality colostrum should be fed as soon as possible after birth and another 2 L should be fed within 12 h after calving. Colostrum must be provided; if the calf does not drink the colostrum it must be provided via an esophageal feeder.

Besides increasing immunity, there are other components in colostrum that positively affect gut health resulting in increased health and overall performance. Researchers have observed increased milk production in calves that received 4L of good quality colostrum compared to calves fed 2L of good quality colostrum (Table 9.1).⁵ These data indicate that there are other factors in colostrum that can affect future milk production.

TABLE 9.1 Health disorders, and average daily gain of Brown Swiss calves receiving two or four liters of good quality colostrum and their milk yield as cows^a.

Item	2L	4L
Health disorders	8 ^b	5 ^c
Average Daily Gain, kg/d	0.80	1.03
Milk yield, kg		
First lactation	7,848 ^w	7,526 ^w
Second lactation	8,167 ^w	9,516 ^x

^a 37 Brown Swiss heifers received 2 L and 31 heifers received 4 L of good quality colostrum. 28 heifers fed 2 L and 27 heifers fed 4 L became lactating cows.

^b Pneumonia ($n = 3$), ulcers ($n = 2$), and poor health ($n = 3$).

^c Coronavirus ($n = 4$); navel infection ($n = 1$).

^{w,x} Means in the same row with different superscripts differ ($P < 0.05$).

Adapted from Faber et al., 2005.⁵

Environmental effects on colostrum

The temperature in which prepartum cows experience appears to have an effect on colostrum quality and production. In the development of a model to predict colostrum quality, days above 25°C increased colostrum quality.⁶ In the laboratory, IgG concentration is typically determined using radial immunoassay. A similar result was observed in heat stressed cows, however, these researchers found that while colostrum quality was similar in heat stressed and cooled cows the absorption of IgG by their calves was less.⁷ Cows in this experiment experienced similar temperature humidity indexes, but cooled cows had access to sprinklers and fans while heat stressed cows did not. This effect carried over into reduced weaning weight and milk production when the calves began to lactate. These data indicate that while the increased environmental temperature (>25°C) may increase colostrum quality⁶ it reduces the uptake by the calves.⁷ Therefore, providing cows with shade and fans as a means of heat abatement will enhance the uptake of IgG and possibly other beneficial nutrients and growth factors.

Breed and parity effects

There are breed effects in regards to colostrum quality, typically Holstein cows produce lesser quality colostrum than Jersey cows. This is likely due to a dilution effect of colostrum in the Holstein. Generally, first parity cows also produce lesser quality colostrum. This is likely due to first lactation cows having a more naïve immunity in comparison to cows with more parturitions. It appears that this is becoming less of an issue through improved nutrition of these cows prior to parturition. Recently, it has been observed that the Jersey breed will produce very little colostrum during the winter months in the northern hemisphere.⁸ The effect was observed more for cows with greater than one parity and appears to be correlated with photoperiod (day-length).

Pasteurization

Pasteurization of colostrum will help reduce the number of bacteria present in colostrum. The process typically involves heating colostrum for 60 min at 60°C. Results indicate that the process will reduce the IgG content by 9%–12% while tending to increase the uptake of IgG by the calves.⁹ These results are likely due to the removal of bacteria that can bind to the IgG thus freeing them up for absorption.

Colostrum replacers and supplements

Often, dairy herds may be deficient in colostrum and must resort to feeding a colostrum replacer. Research indicates that this is appropriate if the replacer is colostrum-based (dehydrated) and reconstituted according to directions. However, it appears that while replacers are available they do not function as well as lacteal-based colostrum replacers. Colostrum supplements should be avoided as they show little benefit on the day of birth however they may be of some benefit providing local immunity in the first day of life.¹⁰

Storage of colostrum

Colostrum can be stored and used for other calves when quality is poor or yield is low. Colostrum should be harvested, quality determined (using a refractometer or colostrometer), and stored in 2 L bottles. Colostrum can be frozen for up to one year. Frost-free freezers should be avoided as the removal of frost involves the internal temperature getting above freezing which may denature the Ig in colostrum. Thawing frozen colostrum should be done gradually; avoid heating too quickly as this may denature the Ig. Placing the frozen colostrum in a warm water bath should suffice.

Milk and milk replacer feeding

Beginning on the day after birth, milk or milk replacer is fed to calves. Traditionally milk was fed after morning and evening milking at a rate of 4 L per day. This feeding rate has also been applied to milk replacer. Milk replacer is a milk-based powder that must be reconstituted to approximately 10%–15% solids. More recently, milk and milk replacer feeding rates have increased to 6 L for Holsteins. New technology has developed where calves are allowed to suckle essentially at will. Upwards of 10 L per day is common with these feeders.

Milk in the digestive tract

When a calf consumes milk, a modification of the preruminant forestomach occurs resulting in the formation of the esophageal groove. This groove forms causing milk to bypass the forestomach to the abomasum for digestion.

Milk contains two types of protein, casein and whey. The presence of the enzyme, renin, in the acidic environment of the abomasum in the preruminant calf, results in casein forming a clot which is slowly degraded over the day. Whey does not form the clot and quickly dissociates for passage to the small intestine for further

digestion and eventual absorption of amino acids, di and tri-peptides, and other nutrients.

Milk replacer types

Milk proteins are divided into two classifications, whey and casein. Casein is used for the manufacture of cheese and is removed from milk leaving whey as the primary protein source in milk replacer. A major difference between whey and colostrum is that whey does not clot within the abomasum. The typical milk replacer contains 20%–22% protein and 20% fat on a dry basis. There has been a development of higher protein milk replacers (up to 32% protein) while fat concentrations have been reduced to 16%. These milk replacers are often fed free-choice through automatic feeders as described above.

Other protein sources for milk replacer have been evaluated. These include partial replacement of the whey protein with blood plasma, egg protein, soy protein concentrates and isolates. Some of these sources such as egg protein and soy protein concentrates or isolates are effective alternatives for whey protein generally making up no more than 50% of the protein in the milk replacer. Caution needs to be considered when using these non-milk protein sources because they can result in diarrhea.

Calf starter grain

For the rumen to develop, it is essential that calves consume a highly palatable source of solid feed (calf starter grain). This is essential because rumen fermentation must occur for the rumen to develop. Bacteria which are present from transfer via the dam and from the environment ferment the solid feed and produce volatile fatty acids (VFA). The four carbon VFA, butyrate, is the most important for rumen epithelial (papillae) development. Feeding starter is necessary for this to occur. Because grain ferments at a faster rate than forage, it is not necessary to feed

hay at this stage of life. Typically calf starter contains whole or crimped or steam-flaked grains along with a pellet. Some starters are completely pelleted and good quality hay must be fed.

Water

Calves need to be fed free-choice water along with milk or milk replacer. Due to a physiological adaptation, milk or milk replacer is shunted past the rumen to the abomasum through the formation of the esophageal groove. Water consumption does not cause this to occur unless it is fed immediately after milk or milk replacer feeding resulting in the water entering the rumen, this is essential for bacteria to ferment the solid feed and produce VFA. It was observed that calves deprived of free-choice water consumed 31% less starter and gained 38% less than calves that had free access to water.¹¹

New developments in calf feeding

Milk replacer feeding has changed in recent years with the development of higher protein milk replacers (up to 32%). This is sometimes referred to as the accelerated feeding program. Also with the development of self-feeders, calves have been observed to consume upwards of 10 L of reconstituted milk per day. Results are fairly consistent with growth rates exceeding approximately 300 g/d greater in calves fed a 28:20 (protein: fat) at about 1.3 kg of milk replacer powder/d compared to calves receiving 560 g of conventional (22:20) milk replacer powder (750 vs. 460 g/d respectively).¹² However, weaning can be difficult when calves are fed such a nutrient dense and large amount of milk powder. Weaning is typically determined by measuring how much starter grain the calf is consuming (227 g/d for three consecutive days). Often calves receive half of their milk replacer for 7 days. This forces the calf to consume more of its nutrients from the starter.

Consequently, this is often a stressful time in the calf's life. There has been a large amount of research conducted to evaluate how calves can be effectively weaned with reduced stress. This has led to utilizing a step-down procedure where calves are provided less milk replacer over several days. Calves fed the high protein milk replacer gained only 80–150 g/d compared to the conventionally fed calves who gained approximately 640 g/d during this period.¹² After weaning, there were no differences in average daily gain regardless of treatment. One aspect of feeding high quantity and high protein milk replacer is the necessity to feed water. While milk and milk replacer is effectively shunted past the rumen, water consumed by the calf will go directly into the rumen. However, if the water is not provided, calves can become dehydrated due to osmotic balance being compromised from the high protein and mineral content provided in the milk replacer. Research has shown that water intake was increased when calves were fed the accelerated milk replacer program compared to calves fed a conventional milk replacer feeding regimen.¹³

Researchers have recently attempted to connect average daily gain or intake with future milk production. Some researchers have observed that mammary gland milk-producing tissue was 5.9 times more in calves fed higher levels of milk replacer based on metabolizable energy suggesting that greater protein from milk replacer consumption was beneficial to mammary gland development during the pre-weaning phase.¹⁴ Evaluating data from a university herd and a commercial herd also showed that increased average daily gain during the pre-weaning phase translated into more milk when the calves became cows between 850 and 1,113 kg of milk for every additional kg of preweaning gain.¹⁵ Other researchers have evaluated feed intake as it pertains to future production. Researchers evaluated nine studies and found that during the pre-ruminant phase average daily gain between 0.3 and 0.5 kg/d had little effect on future milk

production.¹⁶ However, they found that first-lactation milk yield was enhanced when the pre-weaning average daily gain was between 0.5 and 0.9 kg/d. These researchers also found that other farm management variables affected first-lactation milk yield.¹⁶ In another study, researchers observed that for every 1 kg of average daily gain during the first six to eight weeks of life translated into an additional 544 kg of milk in first-lactation.¹⁷ Unlike the other study,¹⁵ calves in this data set were fed a conventional milk replacer (22%: 20%).¹⁷ In conclusion, optimizing growth during the pre-weaning phase will likely increase future milk production.

Feeding the post-weaned heifer

To take advantage of the growth realized during the pre-weaning phase it is critical to feed the post-weaned heifer correctly. Goals to be obtained is to feed these heifers so they weigh about 55% of their calving weight at breeding (13–15 mos) and 82%–85% of mature weight at parturition (22–24 months). While most farms do not have scales, utilizing weigh tapes are an accurate way of determining heifer body weights. Also, measuring withers heights may be another easy way of determining the size according to breed. Generally, heifers that are taller at the withers at calving produce more milk than shorter heifers.¹⁸ Nutrient requirements for the large-breed heifer vary as the heifer grows and when she becomes pregnant at around 400 kg (Table 9.2). Typically these heifers are fed a high forage diet as forages can typically meet these nutrient requirements. However, recently researchers found that feeding according to the NRC¹⁹ data set, the maintenance requirements were overestimated by up to 30%.²⁰ It was observed that the growth rates of heifers in a study from preweaning through calving required less ME than the NRC (2001) suggested.²¹ These data suggest that the NRC¹⁹ overestimates the energy requirements for

TABLE 9.2 Nutrient requirements of large breed heifers gaining 0.9 kg/d^a.

BW, kg	DMI, kg/d	ME, Mcal/d ^b	CP, %	Ca, g/d	P, g/d
150	4.2	9.9	16.9	33	15
200	5.2	12.3	15.0	37	17
250	6.2	14.6	13.7	37	17
300	7.1	16.7	12.9	38	18
350	8.0	18.8	12.3	40	19
400	8.8	20.7	11.8	41	20
450	10.4	25.2	14.7	58	28
500	11.3	27.2	14.1	59	29
550	12.1	29.1	13.7	61	30
600	13.0	30.9	13.3	63	31
650	13.8	32.7	13.0	64	32

^a Adapted from Tables 14.13 and 14.15 from NRC. Nutrient Requirements of Dairy Cattle. 7th Rev. ed. National Acad. Press; 2001.

^b ME = metabolizable energy.

post-weaned heifers. Immediately postweaning, the tissue energy content of gain is the lowest of any point during the growth phase.²⁰ These authors state that this is because the rumen and gastrointestinal tract would gain the most mass as it develops to process solid feed.²⁰ As the animal grows up to 350 kg, protein in gain (g/kg) remains flat, but fat in gain (g/kg) increases except at weaning because of rumen development as described above.²⁰ Through a series of equations, it can be calculated that a 219 kg heifer requires 2.16 Mcal of net energy of gain. This accounts for the body composition relative to maturity. Without accounting for maturity the requirement is estimated to be 2.69 Mcal of net energy of gain as suggested by the NRC.¹⁹ Feeding at this rate (2.69 Mcal) would result in overly fat heifers. The equations indicate that a large-breed heifer should gain 0.87 kg/d during the post-weaning phase.

When calves are fed a high energy diet, there is a concern that there is increased mammary gland fat deposition during the prepubertal

phase (<9 months).²² However, by reducing the amount of gain realized to 0.87 kg/d, problems of increased fat deposition in the mammary gland should be limited.

Precision feeding

Recently, the idea of precision feeding of post-weaned heifers has been developed by researchers at Pennsylvania State University.²³ The following is a review of the practical aspects of the precision feeding concept. The concept of precision feeding is providing exactly what the heifer needs to reach its growth requirements. Precision feeding has many benefits to the producer including less chance of over-conditioned heifers, decreased feed costs, and less waste production. Growth is targeted at 0.8 kg/d while meeting all the needs of the post-weaned heifer. Over the entire period, crude protein is set at 14%–15% for heifers, while metabolizable energy ranges from 3.01 Mcal/kg to 2.84 Mcal/kg of intake as the heifer grows (Table 9.3). Neutral detergent fiber ranges from 23% to 35% and all minerals and vitamins are similar to the requirements in the NRC.¹⁹ When precision-feeding heifers, adequate bunk space is required because all heifers need to be able to eat at the same time because they will likely consume their entire daily feed allotment in 1 h. Adequate water intake must be provided. Body weight within a pen should range no more than 90 kg and age variation should be no more than two months per group. Heifers should be taped every time they are handled or at least once a month and diets should be adjusted accordingly. Researchers also recommend that weighing heifers should occur at the same time to account for gut-fill. Bunk space should be between 36 and 61 cm as the animal grows. Avoid wood shavings or straw as bedding as heifers will consume these products. Heifers should be fed the prefresh cow diet 30–45 days before parturition. During this time gut volume will increase without problems.

TABLE 9.3 Nutrient recommendations of precision-fed dairy heifers fed to gain 0.86 kg/d.

Age, mo	Body weight, kg	DMI, kg/d	ME, Mcal/d	CP, kg/d	NDF, %
4	113	2.59	7.8	0.41	23
6	159	3.38	10.1	0.50	24
7	204	4.11	12.2	0.63	26
9	249	4.82	14.1	0.72	27
11	295	5.49	16.0	0.82	28
13	340	6.14	17.9	0.91	29
14	385	6.78	19.6	1.00	30
16	431	7.40	21.3	1.09	30
18	476	8.00	23.0	1.18	31
20	521	8.60	24.6	1.27	32
21	567	9.18	26.2	1.32	32
23	612	9.76	27.7	1.40	33

Adapted from Penn State Extension. Precision Feeding Dairy Heifers: Strategies and Recommendations. Sejrnsen K, Huber JT, Tucker HA, et al. Influence of nutrition on mammary development in pre- and postpubertal heifers. J Dairy Sci. 1982;65:845–855.

Nutrition of the dairy cow

Diet formulation for the high producing dairy cow requires knowledge of the nutrients that are required by the mammary gland to produce milk. These nutrients include water, protein (amino acids), carbohydrates, fats, minerals, and vitamins. Understanding of their physical characteristics and their combined interactions are essential to successful dairy cattle feeding.

Water

Water is second only to oxygen as the most important element for life.²⁴ Milk is 87% water and is critical for milk production. Water makes up between 56% and 81% of total body weight in the dairy cow²⁵ and between 68% and 72% in the preruminant calf.²⁶ Water is essential for the

transport of substances around the body, temperature regulation, insulation, and removal of wastes. As described earlier, water is essential for rumen microbial development in the preruminant calf and ultimately critical in the conversion of the calf from non-ruminant to ruminant (see calf and heifer section). Sources of water are either free-water (drinking water), feed water and water from endogenous reactions. The major source of water for cattle is free water intake. Therefore, anything that limits free water intake will hamper animal performance. As would be expected, free water intake increases as milk production increases. Water intake also increases when the cow is in an environment where the temperature humidity index is above 68. According to the equation of Murphy et al.²⁷, free water intake ranges from 92 to 138 L/d. This equation accounts for feed intake (dry matter), milk yield, sodium intake, and minimum temperature. Recently, Appuhamy et al.²⁸ derived two equations that are now considered the equations to use when estimating free water intake for lactating cows. According to Kononoff²⁴, these equations are now recommended for determining free water intake. Eq. (9.1) utilizes dry feed intake, while Eq. (9.2) utilizes milk yield. Both are adequate in determining water intake.

$$\begin{aligned} \text{L/d} = & -91.1 + 2.93 \times \text{DMI} + 0.61 \\ & \times \text{DM}\% + 0.62 \times \text{NaK (combined} \\ & \text{concentration, mEq/kg DM)} \\ & + 2.49 \times \text{crude protein}\% + 0.76 \\ & \times \text{mean ambient temperature (}^\circ\text{C)} \end{aligned} \quad (9.1)$$

$$\begin{aligned} \text{L/d} = & -60.2 + 1.43 \times \text{milk yield} + 0.64 \\ & \times \text{NaK (mEq/kg)} + 0.83 \times \text{DM}\% \\ & + 0.54 \times \text{mean ambient temperature} \\ & + 0.08 \times \text{days in milk} \end{aligned} \quad (9.2)$$

Contaminated water with bacteria, minerals, and toxins will affect production in dairy cattle. It is recommended that the water meets the

recommendations for minerals, total dissolved solids, and bacteria as presented by Kononoff.²⁴ Water can also provide minerals which can either disrupt the performance of lactating cows while enhancing the health of prepartum cows. Prepartum cows are often fed an acidogenic diet which is augmented by chlorine and sulfur. When balancing acidogenic diets, it is recommended to account for the water intake of these minerals which will help in the reduction of hypocalcemic disease. Conversely, acidogenic diets or water containing Cl and S could reduce lactational performance in cows.

Stray voltage can be problematic on dairy farms. Cattle are very sensitive to electricity and will often reduce intakes of water and therefore feed when they experience stray voltage through their water source. Observations of stray voltage can be but are not limited to cattle testing the water with their tongues before they drink and lapping water while they drink. Finding the source of electricity and mitigating the problem is critical to maintaining cattle performance.

Water requirements Mature dairy cattle should have access to 4 inches of linear water space, but no less. While this is a small space per animal, it is sufficient because all cattle do not drink at one time if they have continual access to water. Dairy cattle on pasture should have access to free-choice water at all times. Failing to provide adequate water will reduce production and result in feed intake.

Protein and amino acids

Protein is typically measured in feedstuffs as crude protein (CP) which is defined as the %N in a feed multiplied by 6.25. The value 6.25 is derived from the fact that feed proteins contain approximately 16% N. However, crude protein contains not only true protein, but other N containing compounds such as amino acids, dipeptides, nucleic acids, $\text{NH}_3\text{-N}$, and other non-protein nitrogen (NPN) compounds. It also

needs to be realized early on that cattle as with all animals do not have a protein requirement, they have an amino acid requirement and true proteins are defined as chains of amino acids. Cattle can use amino acids for the production of enzymes, milk proteins, immunoglobulins, muscle and various organs and tissues in the body. Excess amino acids can be used in some instances for gluconeogenesis and lipogenesis. The production of milk proteins is needed for the production of bioactive proteins present in the whey portion of milk which have several protective functions for the neonate. The production of casein and whey protein provides the amino acids necessary for growth in the young.

Amino acids

There are hundreds of amino acids in nature. An amino acid contains both amino and acid groups. In most animals, there are ten essential amino acids with the remainder considered non-essential. That said, there are some amino acids that are considered limiting for production. These limiting amino acids are based on the diet fed to the cattle. For instance, in the US, corn and soybean meal are the primary sources of energy and protein in dairy cattle diets. Corn is usually fed in two ways, as silage, and as a grain. Corn is known to be deficient in the essential amino acid lysine. Soybean co-products are typically the primary protein supplement supplemented with corn feedstuffs. Soybean feedstuffs are deficient in the amino acid methionine. Therefore, these amino acids (lysine and methionine) are considered to be co-limiting in US dairy diets.¹⁹ This means that protein synthesis and yield are limited by the amount of these amino acids in the cow's diet. Supplementing other essential amino acids will not compensate for these. Typically, a source of protein that will be undegraded in the rumen (such as blood or fish meal) and high in these particular amino acids will be included in the diet to help compensate for the deficiency. Diets fed to cows that are high in grass silage and pasture with barley and oats such as those found in Northern Europe

typically will be adequate in Lys and Met, but deficient in histidine.²⁹

Protein synchronization

Crude protein is typically divided into two portions rumen undegradable protein (RUP) and rumen degradable protein (RDP).¹⁹ The RUP fraction will bypass the rumen and pass to the small intestine for digestion similarly to that of non-ruminants. The RDP fraction has several fates – it is typically degraded to amino acids, dipeptides, and ammonia by the microbes present in the rumen. Excess ammonia in its unionized form can be absorbed across the rumen wall and transported to the liver via the hepatic portal vein for detoxification to urea. Urea will enter the blood and can be present in the blood, milk, and other bodily secretions. Urea can also be recycled through saliva and back into the rumen for potential reusing by the microbiome. As described in the carbohydrate section, fermented carbohydrate can be utilized by bacteria along with ammonia to make bacterial protein. Cellulolytic bacteria need ammonia to optimize their ability to digest fiber. However, protozoa cannot use ammonia as a source of nitrogen and therefore must acquire their amino acids through the absorption of free amino acids or through the engulfment of bacteria.

Metabolizable protein

To more accurately consider the utilization of protein by the cow, the use of metabolizable protein (MP) is warranted. This represents the amino acids which are absorbed by the cow in the small intestine. It is comprised of RUP (rumen undegraded feed protein), microbial crude protein (bacteria and protozoal protein) along with endogenous protein (sloughed cells). This RUP is the protein that is subject to proteolysis and eventual digestion to amino acids which can be absorbed across the small intestine. Amino acids get absorbed by enterocytes in the small intestine, and get transported to the liver for utilization in that organ or transported to various tissues for use (growth, lactation, etc.).

Rumen-protected amino acids

To meet the needs for amino acid deficiency, research has been conducted evaluating the use of rumen-protected amino acids (RPAA). The major amino acids researched are methionine and lysine with much research showing benefits to protein yield along with milk yield.¹⁹

Future directions

A concern of overfeeding protein is the amount of N that enters the environment; therefore, researchers have conducted research to reduce the amount of N lost to the environment while optimizing N usage within the cow. The research includes optimizing RDP and RUP and further developing research with the use of MP and RPAA to reduce environmental effects (both ammonia volatilization and waste streams).

Recommendations

Lactating cows should be fed an array of protein sources instead of one type. For example, corn distillers and corn gluten meal are both derived from corn, therefore lactation performance could be improved by adding soybean and/or canola protein sources. It is suggested that % RDP should be close to 10% while % RUP can be 5.5% to 6.0 % dietary DM.¹⁹

Carbohydrates

Carbohydrates are nutrients based on carbon, hydrogen, and oxygen. There are more oxygen molecules in carbohydrates than lipids. They are also the largest component in the diet of dairy cattle. Comprising up to 70% of the diet of lactating dairy cattle and more in that of growing heifers and non-lactating cows. Carbohydrates are typically described as sugars and chains of simple sugars. The two most common carbohydrates used in feeding dairy cattle as with other ruminants are cellulose which are β 1,4 linked glucose units; whereas starch is comprised of α 1,4 (amylose), and α 1,4 and α

1,6 (amylopectin) glucose units. Cellulose is much more resistant to digestion than starches. Therefore, the primary difference is the type of bonds between the glucose units.

Sources of carbohydrates include forages, roughages, grains, and sugars. Forages including hay, hay-crop silage, grain-based silage (corn or small grains) are primarily digested by cellulolytic bacteria which result in the production of acetic and butyric acid. Forages are typically fed with adequate particle size (>3/8 inch) to provide for rumination (the process of regurgitation of cud and the remastication of the forage). This function results in the production of saliva which contains a buffer to help maintain rumen pH (approximately 6.0–6.5). Maintaining H⁺ concentration at this amount will help maintain greater numbers of ruminal bacteria and protozoa. An acidic environment (defined as a prolonged time under pH 6) results in lesser numbers of bacteria and poorer feed digestibility. If acidic conditions are prolonged in the rumen, milk fat depression can occur along with laminitis due to histamine from dead ruminal bacteria toxins congesting in the hoof. Therefore, providing adequate forage can optimize rumen health. Roughages can be forages, but can also include byproducts such as hulls from soybeans and cottonseeds. Some byproducts can provide ample NDF but are of small particle size and contribute little to saliva production from rumination.

Carbohydrate types

In dairy cattle nutrition, carbohydrates are divided into two fractions: structural carbohydrates and related compounds (cellulose, hemicellulose, and lignin), and non-structural carbohydrates (starches and sugars). Lignin is not a carbohydrate but is part of NDF. Structural carbohydrates are typically expressed as neutral detergent fiber (NDF). Neutral detergent fiber is that material that remains after digesting a dried and ground sample in boiling, neutral detergent solution for 1 h. The material

will comprise of cellulose, hemicellulose, lignin, and any N bound to the fiber. The recommended concentration of NDF to feed is close to 27%–28% of the diet DM for lactating cows.¹⁹ Primary sources of NDF are hays, silage, pasture, and roughages. Acid detergent fiber (ADF) is what remains after NDF is boiled in acidic detergent solution for 1 h. In this process, hemicellulose is lost and cellulose and lignin remain. Therefore $\text{hemicellulose} = \% \text{NDF} - \% \text{ADF}$. There are different ways to determine lignin content including heating in KMnO_4 , or 72% H_2SO_4 . Klason lignin is the difference between the residue after acid hydrolysis and the ash remaining after heating the residue in a muffle furnace at a high temperature for 3 h (ash). These remove the cellulose and leaves the remaining lignin. Therefore, $\text{ADF} - \text{lignin} = \text{cellulose}$. Lignin is not appreciably digested and increases as the plants mature. Lignin and ADF are negatively correlated with digestibility. Therefore, it is appropriate that dairy producers harvest forage early in their growth cycle (grass-pre-boot, legume pre-bud) to take advantage of higher digestibility.

Non-structural carbohydrates (NSC) are primarily made of starches (amylose and amylopectin) along with simple sugars and disaccharides. Starches and sugars are typically enzymatically analyzed. However, non-fiber carbohydrates (NFC) which is similar can be estimated by difference using the following equation: $\text{NFC} = 100 - (\% \text{ crude protein} + \% \text{NDF} - \% \text{ neutral detergent insoluble crude protein}) + \% \text{ ash (minerals)} + \% \text{ ether extract (lipids and waxes)}$. Non-fiber carbohydrates include pectins which serve as a cellular glue. This highly digestible component in the rumen is not determined when starches and sugars are enzymatically analyzed. Therefore, pectin is classified as a dietary fiber and is common in beet pulp and citrus pulp. Typically non-structural carbohydrates should provide about 35% of diet DM in a lactating cow, much less in a far-off dry cow or post-weaned, growing heifer.

Microbial fermentation

Microorganisms which reside in the forestomach of ruminants ferment carbohydrates to produce end products called volatile fatty acids (VFA). These VFA are used as energy sources by the cattle. The primary VFA for cattle are acetic acid, propionic acid, and butyric acid. Acetic acid (2 carbons in length) and butyric acid (4 carbons in length) are used for milk fat synthesis in the mammary gland of the lactating cow, while propionic acid (3 carbons in length) is primarily used for glucose. Glucose is the primary precursor of the disaccharide lactose which is the major osmol-regulator of milk. An increase in the concentration of lactose results in an influx of water into the mammary gland resulting in increased milk yield.

Carbohydrate and protein utilization in the rumen

As bacteria digest and ferment carbohydrates, VFA and carbon skeletons are formed. In addition, a portion of feed protein is degraded in the rumen by microbes. Ruminal bacteria can take the ammonia from protein degradation and the carbon skeleton from fermentation and produce amino acids and more bacteria. This utilization of carbohydrates and protein increases the production of ruminal bacteria as well as their passage to the small intestine for digestion and amino acid absorption. This protein is primarily of bacterial in origin, but can also be protozoal. It is known as microbial crude protein and provides part of the metabolizable protein. Providing adequate fiber will enhance the buffering of the rumen providing for a more hospitable environment for the microbes to flourish.

Carbohydrate processing

Processing of forages through rollers at the time of harvest will help to expose the contents of the seed (starch) and the hemicellulose of the stalks. This processing will aid in the

fermentation of the silage in the silo, but also enhance the digestibility of the internal contents of the plants (starch and hemicellulose).

Processing starch is typically done mechanically through hammer mills or grinders to expose the starch to the rumen microbiota. Steam flaking of starch sources results in the gelatinization of starch making it more digestible in the rumen. The production of fermented grain (high-moisture corn), is the process where corn grain is harvested at 75% DM and packed in a silo. The process of packing will expose the internal contents of the seed to microbial fermentation, resulting in the production of lactic acid to prevent deterioration. The energy of the grain will be released due to the fermentation of the grain.

Energetics

The primary sources of energy (calories) to dairy cattle are carbohydrates. The energetics in dairy diets can be divided into several categories and equations from the analysis of various components.

Gross energy (GE) is defined as the number of calories required to increase one mL of water 1 °C. It is defined as the total chemical energy measured from the complete combustion of the material in a bomb calorimeter. For carbohydrates, GE is equal to 4.1 cal/g; while fat = 9.4 cal/g.

DE (digestible energy) = $GE - \text{fecal energy}$ (energy lost in the feces).

ME (metabolizable energy) = $DE - (UE$ (energy in urine) + gaseous energy).

NE (Net energy) = $ME - \text{Heat increment}$.

NE is typically calculated and can be partitioned to NE of maintenance, growth, lactation, etc. The equations to calculate NE of lactation (NE_l) vary based on the type of feed being evaluated whether they be forages or grains. However, regardless of feed type, the % ADF of the diet will negatively affect the NE_l .

Recommendations

It is suggested that most cows be fed diets containing greater than 50% of the diet as forages, however, this can vary significantly depending on the inclusion of fibrous byproducts. However, there are instances where more forages can result in adequate production. Heifers and dry cows are fed diets with a much greater proportion of forages than lactating cows due to the lesser nutrient requirements of cattle in these life-phases. Producers need to strive for the highest quality forage as it dictates the purchase of commercial grains and supplements. Higher quality forages (lesser NDF) will result in decreasing the need for purchased feeds and enhance the farm's profits.

Fat

Fat comprises the most energy dense nutrient with 2.25 times as energy than carbohydrates or protein. Fat is not appreciably fermented in the rumen resulting in little heat of fermentation and can help maintain caloric intake especially when cattle are experiencing heat-stress.

Types of fat

Fat can be divided into two types, glycerol and non-glycerol.³⁰ Non-glycerol-type fats have little to no nutritive value and include waxes and sterols; whereas, glycerol-type fats include triglycerides, phospholipids and glycolipids and are of nutritive value.³⁰ These fats contain the glycerol backbone, carbohydrate or phosphate moiety and have long carbon chains. Rumen microbes can incorporate fatty acids into their cell membrane and modify the typical even number of carbon fatty acids into odd C chain fatty acids. Unsaturated fats have double bonds whereas saturated fats are fully hydrogenated. Most plant fats are unsaturated whereas most terrestrial animal fats contain varying amounts of saturated fat.

Rumen-active fats

Fats that are hydrogenated in the rumen can have deleterious effects on rumen microbes resulting in milk fat depression, decreased dry matter intake and decreased milk yield. These negative effects are a function of how rapidly these fats are available to microbes in the rumen. For instance, cottonseeds, or lightly processed feedstuffs (such as cracked soybeans) will not have a deleterious effect due to their slow release. Further processing (reducing particle size) of higher fat feedstuffs will result in negative effects on rumen fermentation. The oil can coat the fiber and reduce fiber digestibility and also result in decreased numbers of microbes.

Incomplete biohydrogenation

When rumen microbes are presented with unsaturated fatty acids they attempt to hydrogenate the double bonds often resulting in isomers that result in milk fat depression.³¹ Various dietary factors such as low NDF, small particle size of fiber, high diet fermentability (high starch), high concentration of unsaturated fat, or more likely, the combination of the factors can result in incomplete biohydrogenation resulting in increased ruminal production of isomers of C18:2 and C18:1 which can decrease milk fat synthesis in the mammary gland.³¹

Rumen-inert fats

Feeding prilled fats (solid at room temperature) will not be hydrogenated in the rumen and will pass to the small intestine for modification and absorption. Fatty acids bound to metal ions (Ca) form soaps and are considered partially protected and will only be moderately broken down in the rumen.

Fat digestion

As fats pass through the rumen and reach the small intestine, absorption will occur once fats are emulsified with the help of lysolecithin and

absorbed as a micelle. These will be transported to the lymph and then to the heart and partitioned to the necessary organ. In early lactation, fats will be transported to the mammary gland and can be incorporated into milk fat thus saving nutrients for use in other synthetic requirements of the mammary gland (lactose) and often resulting in an increase in milk yield. Post-peak milk production, dietary fat will be stored as adipose for use in the subsequent lactation.

How to feed fat

It is imperative to remember that almost all feeds with the exception of water and minerals contain fat. Many lipid-soluble vitamins have isoprenes as their carbon backbones. Carbohydrates typically are associated with about 3% fat with some immature grasses having over 5% fat.³⁰ Protein meals tend to also have around 3% fat depending on how they are processed while some distillers and brewers grains can contain up to 10% fat. Oilseeds (soybeans, cottonseed, canola, flax) typically have approximately 20% fat while some lesser-used oilseeds (sunflower, pumpkin) can have fat content approaching 45%. Recommendations to feed typically indicate not to feed more than 8% of fat in total dry matter. A typical TMR (52 pounds of DM) with no supplemental fat will contain about 3%–4% fat. Adding 5 pounds of common oilseeds will result in an additional one pound of supplemental fat or about 5.4% fat diet. The oilseeds should be cracked for canola, soybean or flax, but left whole for cottonseed since over processing will result in poor performance by the cows. Adding an additional pound of prilled fat (rumen-inert) will result in a 7.35% fat diet and is typically fed to high producers near peak. As lactation progresses and milk production begins to drop, it is common to remove the inert fat and as a cow enters late lactation, the oilseeds will typically be removed from the diet. It is recommended that calcium level be increased in the diet when feeding fat to 1% of

diet dry matter to reduce any deleterious effects on rumen fermentation.

What to expect

If fat is fed correctly, early lactation cows should see higher milk yields, sometimes enhanced milk fat content, but almost always a reduced milk protein concentration. However, there may be an increase in milk protein yield (kg) due to the increased milk yield. Cows post-peak should see an increase in body condition. Cows should also experience improved fertility through either greater energy balance or improved hormone concentrations involved in reproduction.

Minerals

Minerals are typically classified as metal elements that are inorganic compounds required for many different bodily functions from structure, and nerve impulses to osmotic balance. Some minerals serve as catalysts for reactions or are necessary for enzyme function (e.g. glutathione peroxidase).

Minerals are divided into two categories 1) macrominerals (including Ca, P, Mg, K, Cl, Na, and S) which are required in gram quantities. Microminerals also known as trace minerals are required in mg or μg quantities.

In dairy cattle, mineral nutrition is essential for the success of the lactation. Because of the large amount of milk that cows produce at parturition, there is a large draw on Ca. Often this situation will put the cow into a hypocalcemic state, commonly known as milk fever or parturient paresis. In this state, the cow will have an inability to stand, will have cold ears, and will often have a reduced body temperature. Normally the parathyroid hormone which will respond to low blood Ca causing the bone to release Ca, the kidney will reduce Ca excretion, and the kidney will begin synthesizing 1,25 dihydroxy vitamin D to initiate efficient Ca absorption from the intestine.

In cattle, the blood pH is highly regulated around pH 7.37³². According to Goff³², blood pH depends on three factors: (1) respiration which removes the bicarbonate anion from blood, (2) the balance of positively charged minerals (cations) and negatively charged minerals (anions), and the concentration of blood proteins. Dietary cations especially Na^+ and K^+ , are absorbed at almost 100% efficiency³² and will raise the blood pH. Conversely, Cl^- s also absorbed at 100% and will help to lower the blood pH. In cows suffering from hypocalcemia, blood pH is elevated resulting in the inability of parathyroid hormone from binding to its receptors. Therefore, several equations have been developed that considers the cation-anion difference (DCAD). Many researchers have studied the effect of blood pH on hypocalcemia and it is common to feed anionic salts and reduce the amount of cations fed during the three week period before calving. The DCAD value in dry cow diets is typically < 0 for it to be effective in causing parathyroid hormone to function adequately. However, immediately post-calving a cation-based diet is recommended for cows. This typically can be formulated by feeding legumes which are high in K^+ and through the addition of sodium bicarbonate which aid in buffering the rumen pH and preventing ruminal acidosis. The equation to calculate DCAD is $(\text{meq}/100\text{g DM}) = [(\% \text{Na}/0.023) + (\% \text{K}/0.039)] - [(\% \text{Cl}/0.039) + (\% \text{S}/0.016)]$ ³³

Macrominerals to consider when formulating dairy cow diets

Calcium

Normal blood plasma total Ca concentrations are 9–10 mg % and is tightly regulated.³² Calves, especially preweaned calves, absorb Ca very efficiently (90%). Older animals are less efficient in absorbing Ca, possibly due to reduced 1,25 dihydroxy vitamin D receptors on the intestine which stimulate Ca uptake. Cows experience negative Ca balance until they are post-peak. This is due to the Ca requirement needed for high milk

production. Calcium absorption increases 160% from one day prior to calving until eight days later. The calcium requirement for lactating cows is variable, with a minimum of 0.61% of the diet (DM basis)¹⁹ but can be increased to 1% especially when feeding additional fat in the diet. Besides hypocalcemia, deficiency is rare with a bone deformity known as rickets and osteomalacia in older cows. Besides structure and feed prehension, Ca is needed for smooth muscle function and nerve impulse. Cows that experience hypocalcemia can also experience retained placenta due to the inability for the uterus to contract to release it. Mastitis can also occur as the keratin plug (an antibacterial physical barrier present in the streak canal) falls out due to the relaxation of the muscles within the teat end. This results in the ability for bacteria to enter the teat cistern and gland cistern of the hypocalcemic cow. Other disorders can occur such as ketosis due to reduced gastrointestinal tract motility and low caloric intake. Good sources of Ca include green forages and limestone.

Phosphorus

Phosphorus is present in every cell within the body and almost all energy-dependent reactions involve the formation of breaking high energy phosphate bonds (Adenosine Triphosphate). About 80% is found in bones and teeth. In blood plasma, growing cattle have 6–8 mg P/100 mL and adult cattle have 4–6 mg P/100 mL³². It is required by the cellulolytic bacteria and the synthesis of microbial crude protein. Like urea, P can be recycled through saliva and utilized in the digestive tract. Similar to Ca, P absorption occurs through the function of 1,25 dihydroxy vitamin D or through passive transport when concentrations are high. The synthesis of the active form of vitamin D occurs when blood P is low. The P requirement of the diet (DM basis) for calves is 0.3–0.4% while for cows 0.32–0.42%. It is difficult to cause a P toxicity because excess is excreted. Overfeeding of P has been of concern lately because excess is

excreted and the P which reaches water bodies have caused eutrophication. Therefore, nutritionists strive not to overfeed P. Phosphorus deficiency is very general and can be duplicated for many other minerals. These include poor appetite, poor growth, reduced fertility, and typically poor overall performance.¹⁹ Hypophosphatemia (<2 mg P/100 mL in blood plasma) can occur in cows carrying twins.

Potassium

Potassium is the third most abundant mineral in the body, It is highly regulated with excess lost in the urine. Like Ca, K is high in green crops and also those following K fertilization. Like Na, K is a cation and can exacerbate hypocalcemia, but is beneficial in maintaining a positive DCAD postpartum. In lush pasture or high K diets, a subsequent Mg deficiency can occur (grass tetany) resulting in stiff muscles even when adequate Mg is fed. Potassium is involved in acid-base regulation, water balance, nerve transmission, muscle contractions, oxygen and carbon dioxide transport and a co-factor in many enzymatic reactions. The normal concentration in blood plasma is 3.7–5 mEq/L.³² Potassium is primarily absorbed in the duodenum by diffusion and it is primarily excreted via the kidney in the urine. Lactating dairy cows should be fed a diet containing 1.5% K or more, while calves need 0.4%–0.55%.¹⁹ However, lower K can be beneficial in dry cow diets as a means of reducing hypocalcemia. Potassium toxicity is rare along with K deficiency.

Magnesium

Magnesium is an intracellular cation required for many enzymatic reactions. Its concentration in plasma is around 0.85–1.0 mmol/L.³² In cows absorption of Mg primarily occurs in the forestomach, while in the small intestine in young calves. It is primarily absorbed passively, but also through a Na dependent active transport system. Forages have adequate Mg, but absorption requires Na so feeding Na is

necessary for Mg uptake. The requirement of Mg is 0.2% of diet DM.¹⁹ Deficiency can occur when pastures and feeds contain high amounts of K. Therefore, supplemental Mg is needed especially when high-quality pasture and forages are fed.

Sodium

Sodium is primarily an extracellular cation and can improve animal performance. It is commonly fed as salt and as a rumen buffer. It is a constituent of the equation to calculate free water intake²⁷ and is involved with DCAD. Feeding high amounts of Na during the prepartum period can result in hypocalcemia while feeding it during the postpartum period stimulates water intake, rate of passage through the gastrointestinal tract and therefore feed intake. It functions in maintaining acid-base balance and fluid volume. It is important in the function of the Na–K ATPase which is needed for cation transport in and out of cells. Sodium is absorbed throughout the digestive tract as is thought to be 100%.¹⁹ The requirements of Na are highly variable and is about 0.24% of the diet.¹⁹ Salt deficiency results in pica and usually takes 2–3 weeks to occur. A sign of salt deficiency is the consumption of urine by deficient cows. Salt toxicity can occur if inadequate fresh drinking water is absent, with udder edema and eventual collapse will occur.

Chloride

Chloride is the major anion making up to 60% of the anions in extracellular fluid. It has a strong relationship with K and Na. It is essential for the transport of oxygen and carbon dioxide. It is also the chief anion in gastric secretions needed to begin protein digestion in the abomasum (bound to H).³² The requirement for Cl is 0.34% of diet DM, but if you feed salt to meet the Na requirement you will meet the Cl requirement.¹⁹ It is absorbed across the digestive tract and co-transported with Na across the rumen wall. While toxicity of Cl has not been determined, a

deficiency of Cl results in metabolic alkalosis, fecal mucus, and polyuria.

Sulfur

Sulfur comprises 0.15% of body weight.³² It is found in amino acids such as methionine, cysteine, and taurine. The requirement of S is 0.2% of the diet (DM basis)¹⁹ and it can be included in the DCAD equation as an anion along with Cl.³² Sulfur is also present in thiamin, biotin and chondroitin sulfate. Toxicity can result in neurological changes including blindness, coma, and recumbency. Feeding a 0.5% S diet (DM basis) is common in diets to reduce DCAD. However, feeding higher than this can be considered toxic. Polioencephalomalacia can also occur when high amounts are fed along with interference with Cu and Se absorption.

Microminerals to consider when formulating dairy cow diets

Copper

Copper is part of the cytochrome oxidase system necessary for the electron transport chain. It is involved in the enzyme lysyl oxidase which catalyzes the formation of desmosine cross-links in collagen and elastin necessary for bone strength. It is also involved in ceruloplasmin which is required for Fe transport for hemoglobin synthesis and superoxide dismutase which functions as an antioxidant. Copper requirements are low, a lactating cow requires 0.15 mg/kg of milk.¹⁹ It is only absorbed at 1%–5% in adult cattle, but 70% in newborns.¹⁹ In diets that are high in S and Mo, Cu absorption is reduced.³² Copper is usually fed as a sulfate, but copper chelated to a protein increases Cu absorption. A deficiency of Cu is very distinct with a loss of coat pigment³² especially around the eyes resulting in “spectacle eyes”. Copper has the potential to be very toxic as large amounts get stored in the liver resulting in hemolysis and methemoglobinemia (reduced ability to carry oxygen in the blood). The maximum tolerable factor for Cu is 40 mg/kg of dry matter.¹⁹

Iodine

Iodine is necessary for the production of the hormones triiodothyronine and thyroxin both involved in metabolism and produced in the thyroid gland. Iodine uptake is very efficient with 80%–90% of intake absorbed.³² The requirement of I is at maintenance 0.6 mg/100 kg of body weight.¹⁹ This increases to 1.5 mg/100 kg of body weight during lactation due to thyroxin production. Certain feeds can reduce I uptake and they are known as goitrogens. The first type is cyanogenic glycosides and can be found in common feeds like raw soybeans, corn, white clover, and millet. To correct the deficiency, feed supplemental I at 0.6 mg/kg of dry matter intake. Progoitrins are present in kale, turnips, and mustards and cause I deficiency. Feeding supplemental I will correct the deficiency. Supplemental I can be fed as iodized salt, NaI, KI, or CaI. Deficiency symptoms are very noticeable and appear as an enlarged thyroid gland known as goiter. Other signs include, hairless calves, reduced fertility and decreased immunity. Toxicity occurs at 68 mg/day and appears as nasal and ocular discharge, excess salivation and scaly haircoats.³²

Iron

Iron is a component of heme and is involved in enzymes in the electron transport chain, such as cytochrome oxidase and cytochrome P-450 enzymes.³² It is very difficult to quantitate a requirement since much of the Fe is recycled. A preruminant calf needs about 150 mg/kg of DM while a mature cow only needs 24 mg/kg of DM¹⁹. A deficiency of Fe is very rare but can be found in calves as microcytic anemia due to the failure to produce hemoglobin. This deficiency is very rare in adult cattle suggesting that the Fe in forages might be adequate. Only 0.1% of the dietary Fe is absorbed. Iron is transported bound to transferrin, when not needed Fe is bound to ferritin and excreted. If toxicity happens (as low as 250–500 mg/kg of dry matter

intake) and Fe cannot be transported out of the body, it can build up in tissues resulting in the production of oxygen radicals and ultimately cellular damage. An Fe toxicity can result in a Cu deficiency.³²

Manganese

Manganese is required for the production of superoxide dismutase and can be absorbed efficiently when it is chelated to an amino acid. The Mn requirement is 40 mg/kg of diet dry matter.¹⁹ Toxicity results in silent heats and low conception rates.³² Deficiency can also cause the same effects on fertility as toxicity, but also skeletal abnormalities. The majority of absorbed Mn is transported to the liver and excreted in bile. Manganese is found in bone, liver, and hair. There are no precise requirements for Mn. Deficiency occurs when levels are less than < 20 mg/kg of dry matter³² and toxicity occurs at 1000 mg/kg of dry matter.¹⁹

Molybdenum

There is no requirement of Mo in cattle. However, the maximum tolerable amount is set at 10 mg/kg dry matter.¹⁹ It is a component of several enzymes including xanthine oxidase, sulfide oxidase, and aldehyde oxidase.

Zinc

Zinc is part of several metalloenzymes such as RNA polymerase, carbonic anhydrase and several others that impact nutrient metabolism.³² Zinc absorption primarily occurs in the small intestine. The requirement in the growing heifer is 200–300 mg and 22.8 mg/kg of diet (on a DM basis) in a cow.¹⁹ About 50% of Zn in milk gets absorbed by calves. Deficiency of Zn results in weak hooves, impaired testicular growth, and parakeratosis (scaly skin). Toxicity is difficult to attain with the maximum tolerable level being in the range of 300–1000 mg/kg of diet.³²

Selenium

Selenium is an important component of glutathione peroxidase along with vitamin E. This enzyme is responsible for the conversion of cell-damaging hydrogen peroxide to water.³² Deficiency symptoms were fairly common until supplementation began. White Muscle Disease (WMD) is the common deficiency sign with leg weakness, stiffness, and muscles have chalky striations. Calves with WMD usually die of cardiac failure.

Selenium is highly regulated by the US FDA at 0.3 mg/kg diet supplemental selenium. Supplemental Se reduces the incidence of retained placenta, cystic ovaries, metritis, and mastitis. The absorption coefficient of Se is 30%–65%.¹⁹ When fed to the pregnant cow, Se can pass through the placenta and reduce the incidence of WMD. Toxicity occurs when cattle are fed 5–40 mg/kg of diet for several weeks resulting in blind staggers and sloughing of hooves.

Vitamins

Vitamins are needed for metabolism. They are organic compounds that can be divided into two categories, water-soluble and lipid soluble. Water-soluble vitamins are those that go into solution within an aqueous environment. They are typically synthesized at adequate quantities within the rumen. However, there are some water-soluble vitamins that when supplemented can have beneficial effects. Lipid-soluble vitamins are those which are lipid-based. They are vitamins A, D, E, and K. Vitamin K is involved in blood clotting and is synthesized by the rumen microbes at adequate quantities. Vitamin A, D, and E need various levels of supplementation depending on the diet fed.

Vitamin A

Vitamin A is found in the form of retinol in the animal.³⁴ Vitamin A deficiency results in night-

blindness. Retinoic acid is also involved in gene transcription and cell processes and overall health.³⁴ Typical supplementation is with all-trans retinyl acetate or all-trans retinyl palmitate.³³ Naturally occurring β -carotene also serves as a major precursor it is typically found in green leafy forages such as green-chop or lush pasture. The requirement for feeding dairy cattle is 110.25 international units (IU) of vitamin A/kg of body weight. Feeding twice the requirement is very common due to vitamin degradation and appears to be safe.³⁴ The conversion of β -carotene to 1 mg vitamin A in dairy cattle = 7.3 mg³⁴.

Vitamin D

Vitamin D is an important vitamin and is essential for mineral metabolism specifically Ca. It is responsible for the conversion to 1,25 dihydroxyvitamin D which is involved in the transfer of Ca and P across the intestine. Vitamin D is naturally occurring in cattle that have access to the sun as the active form is made in skin exposed to sunlight. However, with many cows in confinement housing, supplemental vitamin D is essential. About 30.87 IU per kg of body weight is the requirement,¹⁹ again as with vitamin A doubling this amount is likely not to be a concern.³⁴

Vitamin E

Vitamin E is typically found at high concentrations in green forages but is typically supplemented in the form of all-rac- α tocopheryl acetate (1 mg = 1 IU).¹⁹ The function of vitamin E is to serve as an antioxidant with the mineral selenium. Antioxidants protect cells from damage by peroxidases. Therefore, vitamin E is essential for helping to maintain cellular integrity and reduces the effects of any disease that can impact cell health such as mastitis and metritis. Suggested supplementation of vitamin E is 1,000 IU/day for dry cows and 500 IU/day for lactating cows.

Niacin

Niacin has been supplemented to dairy cows with mixed results. It can be found in two forms the amide form (nicotinamide) or the acid form (nicotinic acid). There is very little research evaluating the differences between the two forms. Niacin has been shown in some studies to reduce fat mobilization while not in others and about 12 g/d increases milk yield by about 0.5 kg³⁴. Biochemically, niacin can cause increases in blood flow in some species and can reduce skin temperature and may be suggested to feed to cows experiencing heat stress.³⁴ Recently niacin in the nicotinic acid form has been shown to improve colostrum quality (increased immunoglobulin G) when fed at 48 g/d.³⁵

Biotin

Biotin is another water-soluble vitamin that has experienced use in the dairy industry.

Supplementing cows with 22 mg has been shown to improve hoof health and indirectly milk production through the cow's ability to compete at the feed bunk. It is very common to feed this vitamin to cows in free-stall management situations.

Feed additives

Feed additives are typically added to dairy cattle diets to improve performance such as growth, milk yield, milk component yield, feed efficiency, and health. Their use should be based on unbiased research and their return on investment. This section will describe some common feed additives and their potential response.

Ionophores

Ionophores have been fed to dairy cattle for many decades resulting in improved feed efficiency, reduced coccidiosis in calves and heifers, and reduced incidence of ketosis in lactating cows.³⁶ There probably have been more research evaluating ionophores in

ruminant diets than any other feed additive. They are classified as antibiotics and are produced from the end-products of bacterial fermentation by two bacteria, *Streptomyces cinnamonensis* (monensin) and *S. lasaliensis* (lasalocid). They are active in the rumen by reducing the numbers of Gram-positive bacteria and thereby enhancing the numbers of Gram-negative bacteria causing an increase in the production of propionate. This volatile fatty acid is primarily used by ruminants as the precursor of glucose. Heifers that are fed ionophores have improved growth efficiency (Gain/Feed). Lactating cows fed monensin are less prone to ketosis due to the presence of more propionate and ketosis is essentially a deficiency of glucose. Ionophores disrupt the cell membrane of Gram-positive bacteria resulting in their death. They also work similarly against coccidia in the intestine of calves and heifers and aid in the reduction of this protozoal disease.

Probiotics

There are presently many different probiotics including bacterial species, yeasts, and yeast cultures. These products are thought to enhance nutrient digestibility through increasing bacterial species. Some probiotics can have positive effects in young calves by stimulating local immunity in the small intestine. There are a large number of research studies evaluating yeast and yeast cultures and these are fairly common additives in cow diets.³⁷

Rumen buffers

Another common feed additive found on many dairy farms especially in lactating cow rations is sodium bicarbonate (baking soda). Sodium bicarbonate is thought to increase the pH of the rumen, but it is also involved in enhancing water intake resulting in a greater rate of passage and more feed intake. Up to 227 g is fed, sometimes it is provided free-choice. It is not advisable to feed sodium bicarbonate to dry cows as it can increase DCAD

and stimulate hypocalcemia in those cows. There are some data suggesting that sodium bicarbonate can be fed to heifers resulting in an enhancement of growth rate. Calculating a DCAD of 200–300 mEq/kg is now the recommended method in determining the feeding rate of rumen buffers.

Sodium butyrate

Recent research has shown that sodium butyrate added to calf starter grain can benefit young calves apparently through enhanced rumen papillae development.³⁸ Sodium butyrate is involved in epithelial development in many species. It appears that adding it to milk replacer enhances intestinal development³⁹ while adding it to post-weaned heifer diets enhances feed efficiency.⁴⁰

Essential oils

With the recent regulation in the use of antibiotics in the European Union, researchers have evaluated other feed additives that may serve in enhancing feed efficiency in dairy cattle. These oils are extracts from different plants. The responses up to the date of this chapter are mixed and currently are not recommended to be fed to dairy cattle.

Practical dairy cattle feeding

In the previous sections of this chapter, we have reviewed the different nutrients required for a successful dairy feeding program. It is recommended that the practitioner utilize a ration balancing program to meet the described requirements and recommendations. This section will address the practical implementation of that information. The nutrient requirements of lactating Holstein cows are in [Table 9.4](#).

Diet balancing

In the US, it is common to have different types of feeding situations. Small dairy farms may

TABLE 9.4 Nutrient requirements of lactating dairy cattle.¹⁹

Milk production, kg	25	54.4
DM intake ^a , kg/day	20.3	30.0
Energy, NE _l ^b , Mcal/kg	1.37	1.61
Metabolizable protein, g/d	1,862	3,476
RDP ^c , %	9.5	9.8
RUP ^d , %	4.6	6.9
NDF ^e , % min	25–33	25–33
NFC ^f , % max	36–44	36–44

^a DM intake = dry matter intake.

^b NE_l = net energy of lactation.

^c RDP = rumen degradable protein.

^d RUP = rumen undegradable protein.

^e NDF = neutral detergent fiber.

^f NFC = non-fiber carbohydrate.

have their herds tied up in tie-stall barns and feed the cows individual ingredients (forage, grain, supplement). This is referred to as component feeding while laborious it provides for individualized feeding. In larger facilities, it is common to place cows in various groups by performance, reproductive status, or by parity. For example, cows could be separated into a high production group, medium production group, and a low production group based on milk yield. Or cows could be grouped by reproductive status so that most nonpregnant cows are grouped together. Also, it is common to have young, first-calf cows in a separate pen as older cows can be aggressive to the young cows and limit their time at the feed bunk.

Bunk space

Dairy cows need two feet of bunk space for adequate dry matter intake. This is commonly found in two-row barns (two rows of free-stalls) that are not overcrowded. Three-row barns are also common but reduce bunk space by six inches. It is now recommended that these barns have headlocks or some means of allowing the cow “space”. Open areas with rails or cables

do not provide for cows to be able to eat as cows are hierarchical animals and a boss cow can control a large part of the bunk. Allowing cows access to feed through headlocks decreases this effect.

Water

Water is the most important nutrient and cows need clean, fresh water free of stray voltage or anything that decreases intake (off flavors). To provide for optimal water intake cows need about four inches of water space per head. Waterers should be cleaned routinely, some high producing herds clean that waterers at every milking.

Cow comfort

Since the thermal neutral zone for European cattle ranges from 5 to 20°C, it is a necessity for some type of heat abatement. Fans and misters are common in hot environments, these cool the cows and improve air quality optimizing intake and reduce internal cow heat build-up.

Adequate cow stalls are also important, cows need to be able to lay down for 14 h per day to optimize performance. Providing clean dry stalls is imperative for enhanced milk production.

Consistency

Dairy cattle do not like change. Feeding at the same time and milking at the same time will enhance performance in the herd. Decreasing time away from feed and water (reduced time in the holding areas) will enhance performance. It is recommended that water be available in holding areas to decrease time away from waterers.

Feeding

While it is common to feed once daily, more producers are now feeding at least twice daily. Some producers with high yielding cows feed four times per day. Because cows like consistency, the more a producer feeds, the more likely the cows will eat. It is common to push up feed to stimulate intake. Pushing up feed at least six

times a day is recommended. Some automatic feed pushers work 12 h per day.

What drives intake?

There are three theories describing feed intake by cattle. The first theory is bulk, as NDF in the diet increases, feed intake decreases due to stretch receptors in the rumen wall signaling satiety. The second is based on energy intake. Diets based on high-energy will result in reduced intake when the energy requirement is met. This theory will only work in late lactation and during the dry period when cows can eat to meet caloric requirements. The third theory and the one most likely observed is the oxygen consumption theory. As cows produce more milk, the need for the blood to carry oxygen to tissues is increased, and the heart must pump at a faster rate and consumption of oxygen increases. More nutrients are provided to the mammary gland resulting in a greater need for nutrient uptake and hence greater feed intake.

Dry cow feeding

The lactation cycle of a dairy cow includes a dry or non-lactating phase. The typical lactation lasts 305 days and during this time the cow should get pregnant usually between 60 and 90 days but before 100 days. The dry period typically lasts 60 days during this period the calf is growing and the mammary gland undergoes involution. The diet is typically a high forage diet and the nutrient requirements are in [Table 9.5¹⁹](#). Beginning about 3–5 weeks before the cow is expected to calve, the diet is changed to a higher concentrate diet. This serves several purposes including providing more nutrients to the growing calf and the cow as dry matter intake begins to drop as the cow approaches parturition. Also, the rumen microbiota need to change to reflect the diet fed after parturition. This change in diet also causes the rumen papillae to lengthen resulting in more surface area for nutrient absorption. This can help reduce post calving metabolic disorders such as

TABLE 9.5 Nutrient requirements of dry cows¹⁹
Days Pregnant.

	240	279
DM intake ^a , kg/d	14.4	10.1
NE _l ^b , Mcal/kg	0.97	1.44
Metabolizable protein, g/d	871	810
NDF ^c , % min.	33	33
NFC ^d , % max	42	42

^a DM intake = dry matter intake.

^b NE_l = net energy of lactation.

^c NDF = neutral detergent fiber.

^d NFC = non-fiber carbohydrate.

lactic acidosis and ketosis. These cows are typically fed a negative DCAD (mEq/kg) diet to reduce the chance of hypocalcemia post-calving. Jersey cows seem to be more prone to hypocalcemia than other breeds.

Conclusion

Producing high-quality milk from healthy dairy animals starts with the nutrition and management of the calf. Through proper nutrition and management, the dairy heifer will develop into a high producing dairy cow that can produce to its genetic potential. By providing cows a consistent diet based on their performance along with comfortable housing and adequate water milk production, growth and overall performance should be optimized. Optimizing milk yield will result in a more efficient conversion of feed to milk, consequently enhancing nutrient utilization, reducing waste and helping to maintain a sustainable dairy industry.

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