The process of rumen development and how it impacts our management on the farm

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Introduction

Calves undergo an amazing change from the time they are born until they are adults. One of the most extreme changes is the development of their digestive systems. At birth, the rumen of the calf is small and is nonfunctional. However, within a few weeks, the rumen is the primary site of fermentation and production of energy (as volatile fatty acids, **VFA**) and protein (as microbial protein) for the calf. Development of the rumen also allows the animal to be weaned. Weaning reduces costs associated with rearing the calves and allows the use of forages and concentrates as sources of nutrition. Though rumen development is normal and natural, it is affected by management on the farm. Improper feeding can upset this natural development and predispose calves to weaning stress and disease.

Current Practices in the U.S.

Costs of rearing. Researchers from the University of Wisconsin calculated the costs to raise calves from birth to freshening in the state of Wisconsin (Hagedorn, 2013). They calculated the average cost (across different operation sizes and management types) was USD$ 2,377, including the value of a calf at birth of USD$ 150.

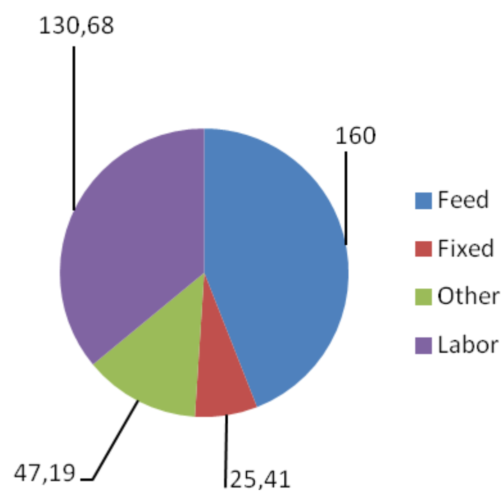

Figure 1. Cost of raising a calf from birth to weaning in Wisconsin. From:

The cost was partitioned into cost of calf and rearing costs from birth to weaning and weaning to calving. Total cost to raise a calf prior to weaning (average 73 days) was estimated as USD$ 363 and primary costs were labor (36% of total) and feed (44%, Figure 1).

After weaning the cost (average 648 days) was USD$ 2,014 (Figure 2). Most cost was associated with feed (57%). The per day cost prior to and after weaning ($5.34 vs. $3.04, respectively) shows clearly that successfully weaning calves from expensive liquid feeds to less expensive forage and concentrates will save the farmer money. Further, the costs of labor and management are lower as are the costs of health treatments.

USDA estimates of weaning. Preparation for weaning requires that dry feed, but particularly calf starter, be available from an early age. The USDA (2014) surveyed dairy farms in the U.S. to determine practices with calf rearing. They reported that the average at which calves are first offered starter, water and forage were 10.8, 17.3, and 36.0 days, respectively. Each of these is far from optimal. Calves are offered starter and water too late and forage too early for optimal rumen development. Thus, many improvements can be made in calf management, particularly on smaller farms (<100 cows) in the U.S.

Average age at weaning was reported to be 9.1 weeks (USDA, 2014). Large operations (500+ cows) generally weaned calves later (8.9 weeks) than small operations (<100 cows; 8.7 weeks). This may be because calves are generally managed in groups on large farms rather than individuals.

Methods of weaning include abrupt or gradual weaning. Abrupt weaning is accomplished by simply ending milk feeding according to a specific criterion - intake, age, etc. Gradual weaning occurs when the amount of liquid offered is reduced for a period of time prior to complete removal of liquid. Often, the amount is reduced by feeding only once daily instead of the normal twice daily feeding for 5 to 7 days prior to complete removal of liquid. This is thought to stimulate dry feed intake while still allowing the calf to obtain nutrients from liquid and, possibly, reduce stress associated with abrupt weaning. Roth et al. (2009) reported that weaning according to concentrate intake reduced the age at weaning from 84 days to 76 days with no effect on health of calves.

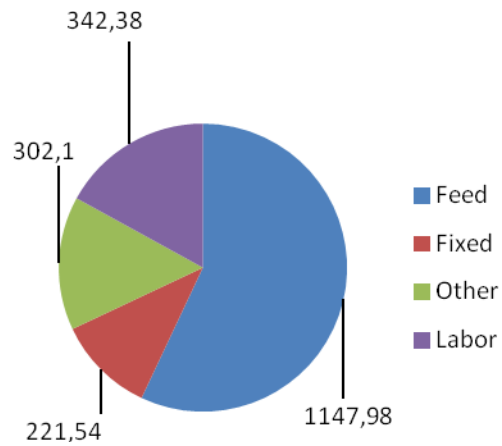

Figure 2. Cost of raising a calf from weaning to calving in Wisconsin. From:

A significant problem associated with weaning according to age is the assumption that calves will consume a sufficient amount of dry feed to stimulate rumen development by that age. Preparation for weaning is a function of **dry feed intake**, not age (see below). Although this relationship between age and intake may be acceptable in most cases, individual calves might not have consumed sufficient feed to allow them to obtain sufficient nutrients from feed after weaning. This can result in stress and predisposition to disease.

Weaning stress is caused by the reduction in energy intake associated with weaning. For example, at 6 weeks of age, a calf may consume 700 grams of calf starter and 450 grams of milk replacer dry matter. At weaning, the calf will receive only 700 ÷ 1150 = 61% of its previous DM intake. The change in ME intake will be greater, since ME is usually higher in milk replacer. This deficit in energy and protein will cause the animal to go into negative energy balance if its starter intake does not increase to make up the difference. In addition, liquid feeding is an inherently pleasurable experience for the animal, and weaning will be associated with stress caused by terminating that experience.

Figure 3. Poor calf starter management. Excess starter will quickly spoil and must be replaced.

Stress at weaning is often exacerbated by performing other management tasks at the same time. Some of these include dehorning, moving the calf into group housing, change in diet (offering different starter and/or hay), removing extra teats, etc. All of these stresses should be minimized at weaning, and should be performed at other times to minimize that stress.

Biological Impact of Weaning. At weaning, the calf undergoes several dramatic changes. Consider the following:

1. The primary source of nutrients changes from liquid to solid
2. The amount of dry matter the calf receives is cut dramatically at weaning
3. The calf must adapt from a monogastric type of digestion to a ruminant type of fermentation and digestion
4. Changes in housing and management often occur around weaning which can add to stress.

Rumen development

At birth, the rumen and reticulum are under-developed, sterile and nonfunctional. Liquid feeds are shunted past the reticulorumen by the esophageal groove. However, by the time the calf is weaned, the rumen is the **primary** compartment of the stomach. It has increased in size, metabolic activity, and blood flow to the rumen has increased. Prior to weaning, the primary source of nutrients is liquid. During the transition period, both liquid and solid feeds provide nutrients to the calf. After weaning, only solid feeds (starter and hay) are available. Before solid feed is consumed, the abomasum is the primary compartment of the stomach and both energy (glucose and fat) and protein are derived from dietary sources. However, by weaning, the rumen has become an important compartment of the stomach, and feed consumed is exposed to bacterial fermentation prior to reaching the abomasum. A net result of this fermentation is a change in the type of energy and protein available to the calf.

Table 1. Composition of the ruminant stomach at various ages.

	Age (weeks)						
Compartment, % of total	0	4	8	12	16	20-26	34-38
Reticulorumen	35	52	60	64	67	64	64
Omasum	13	12	13	14	18	22	25
Abomasum	49	36	27	22	15	14	11

Adapted from Church (1976).

Not only does the activity of the stomach compartments change, but the size of each compartment changes as well. The percent of the stomach as reticulorumen increases from a low of about 38% to a high of 67% by 16 weeks of age (Table 1). Note, however, that by 4 weeks of age, the reticulorumen has increased to 52% of the total stomach capacity. In contrast, the proportion of the stomach as abomasum declines from a high of 49% at birth to a low of 11% after 32 weeks of age. The **absolute size** of the abomasum does not decline - the reticulorumen simply grows at a much faster rate than the abomasum during ruminal development.

Factors Required for Rumen Development

There are five requirements for ruminal development. They are:

1. Establishment of bacteria in the rumen
2. Liquid in the rumen
3. Outflow of material from the rumen (muscular action)
4. Absorptive ability of the tissue
5. Substrate

A number of other metabolic changes occur during ruminal development in the rumen and other tissues, but we will consider the above requirements for the rumen to begin to function. A summary of some changes that take place in the calf are in Table 2.

Table 2. Physiological changes during weaning.

Indicator	Preruminant	Ruminant
Social/Behavioral		
Feeding activity	Suckling	Chewing/ruminating
Esophageal groove	Functional	Non-functional
Liver enzymes[a]	Glycolytic/ketogenic	Gluconeogenic
Substrate/feed	Colostrum, Milk	Water, Starter
Bacterial protein[b]	<30% of total to abomasum	>50%
Rumen Characteristics[c]		
Papillae	Short, narrow	Longer, Wider
Muscularity	Low	Increasing
Volume	Low	Increasing
Blood metabolites[a]		
Energy Source	Glucose	Volatile Fatty Acids
β-Hydroxybutyrate	Low	Increasing
Mammary development[d]	More responsive to high protein	Less responsive to high protein

[a]Baldwin et al., 2004.
[b]Quigley et al., 1985.
[c]Beharka, et al., 1998.
[d]Brown et al., 2005.

Bacteria. When the calf is first born, the rumen was thought to be sterile. However, recent research using new genetic tools has reported that bacteria become established in the gastrointestinal tract very early in the life of the animal. Some researchers have reported that the tract of the animal is implanted with bacteria as the calf travels through the birth canal. Other vectors for bacteria include vaginal secretions, feces and bedding on which the dam lies (Mackie et al., 1999). Many of these bacteria are not normally found in the rumen of the mature animal. However, Jami et al. (2013) reported that mature rumen bacteria could be found in the neonatal calf rumen as early as 1 days of age. As the animal ages and the rumen matures, Jami et al. (2013) reported that the microflora become "*a more diverse but homogenous and specific mature community*."

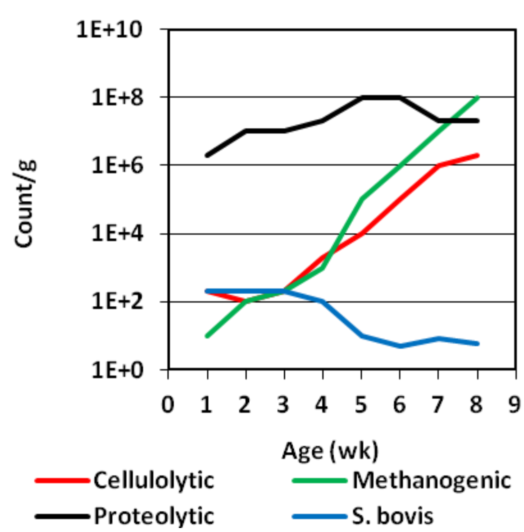

Figure 4. Change in composition of rumen bacteria in calves offered starter from 1 wk.

Kim et al. (2016) reported that the types of bacteria established in the rumen with advancing age appear to be affected by ruminal pH. Inclusion of forage in the diet increases proportions of acetate in the rumen, ruminal pH and promotes an environment suitable for rumen cellulolytics.

However, by one day of age, a large concentration of bacteria (mainly aerobes) can be found in the rumen. Thereafter, the numbers and types of bacteria change as dry feed intake occurs and the substrate available for fermentation changes (Minato et al., 1992; Bryant et al., 1958; Ziolecki and Briggs, 1961). Change in bacterial numbers and types is usually a function of intake of substrate (Lengemann and Allen, 1959; Kim et al., 2016). Prior to consumption of dry feeds, bacteria in the rumen exist by fermenting ingested hair, bedding, and milk that flows from the abomasum into the rumen or leaks into the rumen from incomplete closure of the esophageal groove.

Consumption of fermentable substrate causes dramatic changes in populations of bacteria (Figure 4). Numbers of aerobic bacteria decline and cellulolytic and methanogenic bacteria increase. By two weeks after weaning, the profile of bacteria is similar to that of adult ruminants, even though the size of the rumen remains small. By a few weeks after weaning, the bacterial populations will reflect the fermentability of the diet (Pounden and Hibbs, 1948).

Liquid in the Rumen. To ferment substrate (grain and hay), most rumen bacteria must live in a water environment. Without sufficient water, bacteria cannot grow and ruminal development is slowed. Most of the water that enters the rumen comes from free water intake. If water is offered to calves from an early age, this is not usually a problem; unfortunately, many producers in the U.S. do not provide free water to their calves until calves reach 4 or more weeks of age. Free water has been shown to increase rate of body weight gain and reduce scours (Kertz et al., 1984).

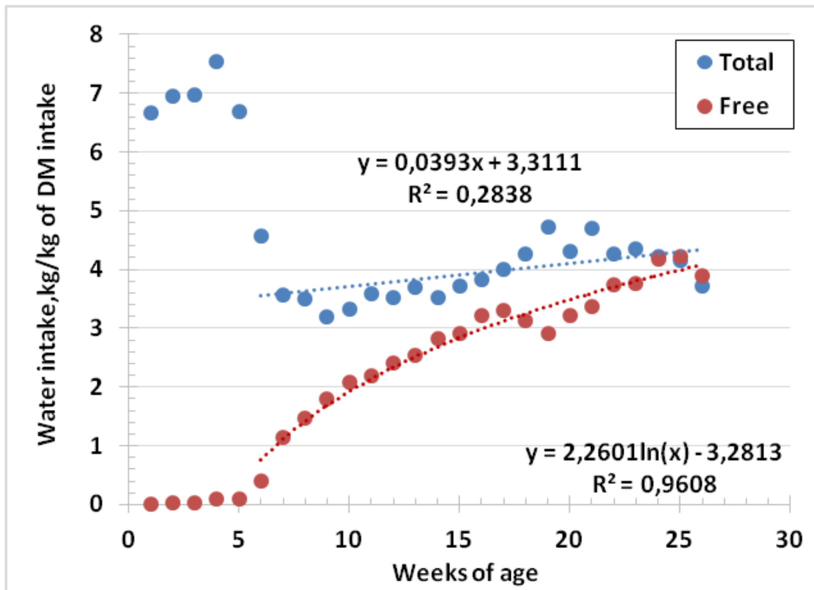

Figure 5. Intake of water as free water (Free) or total water intake (Total) from free water + water in milk + water in dry feed in claves from 2 to 26 weeks of age. From Atkeson et al., 1934.

Milk or milk replacer does not constitute "free water". Milk or milk replacer will by-pass the rumen by closure of the esophageal groove. Closure of the groove is a neural response to feeding. Free water does not stimulate closure of the groove, so water enters the rumen. The esophageal groove closes when the calf is stimulated to consume milk (Wise et al., 1942; Kesler et al., 1956). It is under neural, not physical control. Therefore, position of the head, temperature of the liquid, or other physical factors of liquid management should not affect closure of the groove (Hegland et al., 1957). However, partial closure of the groove or congenital defect can cause some calves to allow significant amounts of liquid enter the rumen. These calves ("rumen drinkers") and experience significant metabolic upset (Herrli-Gygi et al., 2006). Ruminal drinkers are characterized by reduced appetite, pica, enhanced rumination, ruminal acidosis, ruminal hyper- and parakeratosis, ruminal tympany, and increased mortality (Breukink et al., 1988; Van Weeren-Keverling Buisman et al., 1988, 1990; Radostits et al., 2000). Reducing milk and early weaning are recommended whenever possible to reduce the metabolic effects of fermentation of milk on the calf (Radostits et al., 2000).

There have been a limited number of studies evaluating management of water and calf performance. Kertz et al. (1984) suggested that voluntary water intake increases with increasing starter DM intake, at an approximate ratio of 4 L of water per kg of starter. A study conducted in the 1930's supports this observation. Atkeson et al. (1934) monitored water intake (from free water, milk and water in feed) and found that total water intake (kg/kg DM intake) ranged from about 3 to 5 after weaning (Figure 5). The average over all weeks post-weaning was 3.9 L water per kg of DM intake. Wenge et al. (2014) found that calves limit-fed milk replacer consumed 1.1 L of water per day within the first 3 wk of life. Further, calves increased water consumption when they developed diarrhea. Calves fed higher amounts of water as milk replacer will generally consume less free water (Jenny et al., 1978; Quigley et al., 2006), so total water intake appears to be controlled by the animal. However, water intake appears to be more closely associated with rumen development than milk intake per se (Quigley et al., 2006; De Passillé et al., 2011).

Huuskonen et al. (2011) studied effect of warm (16-18°C) vs. cold (6-8°C) water fed to 120 calves from 20 to 195 d of age. Calves were housed in an insulated barn with ambient temperature of 11-20°C in winter (October–April) and 15-23°C in summer (May–September). Calves offered warm water consumed about 8% more water than calves fed cold water throughout the study. The increase in water consumption was particularly noted prior to weaning, when calves drank 47% more water when it was warm. However, there were no effects of water temperature on feed intake, growth or efficiency.

Thomas et al. (2007) reported that adding flavors to water and calf starter promoted additional starter intake and growth in young calves. Conversely, Osborne et al. (2008) reported that addition of 50 g/L of glucose to water did not affect water intake and reduced starter intake. Hepola et al. (2008) offered water in buckets or bottles and found that calves fed via nipples consumed less water and appeared to have more trouble consuming water compared to calves fed via buckets.

We evaluated the factors that affected water intake in preweaned calves that were offered water and starter for free-choice consumption (Quigley, unpublished). The calves were part of seven research trials conducted in Ames, Iowa, USA, during 1999-2000. We collected water and starter intake, ADG, ambient temperature and other measures. Approximately 38,000 daily observations were collected. Using regression procedures, we found that the three factors affecting water intake were starter intake, daily high temperature, and amount of milk replacer fed. Starter intake was most important and accounted for about 67% of the variation in water intake. As starter intake increases, water intake increased, also (Figure 6). We calculated that a calf drank 1 additional L of water for each 500 grams of starter consumed, up to 7 L of water. Similarly, as temperature increased, water intake increased linearly. Finally, as intake of water in milk replacer increased, we found that intake of free water decreased.

Outflow of Material from the Rumen. Proper ruminal development requires that material entering the rumen must be able to leave it. Measures of ruminal activity include rumen contractions, rumen pressure, and regurgitation (cud chewing). At birth, the rumen has little muscular activity, and few rumen contractions can be measured. Similarly, no regurgitation occurs in the first week or so of life. With increasing intake of dry feed, rumen contractions begin (Asai, 1973). When calves are fed milk, hay, and grain from shortly after birth, rumen contractions can be measured as early as 3 weeks of age. However, when calves are fed only milk, rumen contractions may not be measurable for extended periods (Asai, 1973). Cud chewing has been observed as early as 7 days of age, and may not be related to ruminal development *per se*. However, calves will ruminate for increasing periods when dry feed (particularly hay) is fed.

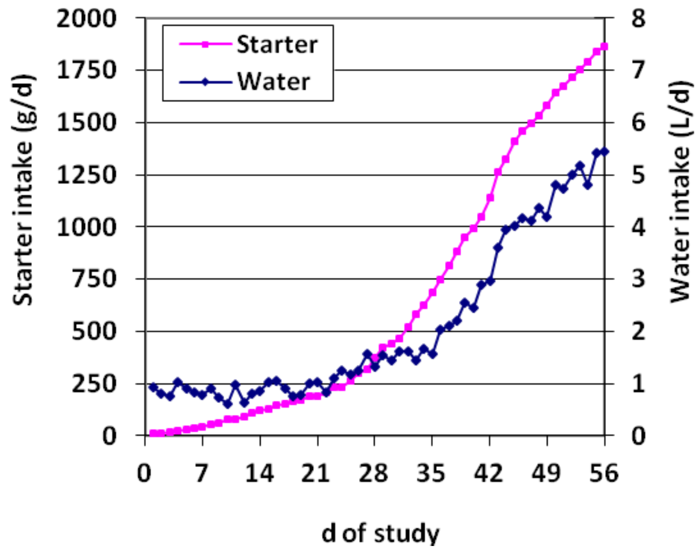

Figure 6. Consumption of calf starter and water in calves housed in individual hutches. Source: Quigley,

Absorptive Ability of the Rumen Tissue. Absorption of end-products of fermentation is an important criterion of ruminal development. End-products of fermentation, particularly the VFA (acetate, propionate, and butyrate) are absorbed into the rumen epithelium, where propionate and butyrate are metabolized in mature ruminants. Then, the VFA or end-products of metabolism (lactate and ß-hydroxybutyrate) are transported to the blood for use as energy substrates. However, there is little or no absorption or metabolism of VFA in neonatal calves. Therefore, the rumen must develop this ability prior to weaning.

Many researchers have evaluated the effect of various compounds on the development of the epithelial tissue in relation to size and number of papillae and their ability to absorb and metabolize VFA (Tamate et al., 1962; Sander et al., 1959; Flatt et al., 1958). Results of these studies indicate that the primary stimulus to development of the epithelium are the VFA - particularly propionate and butyrate (Sander et al., 1959). Milk, hay, and grain added to the rumen are all fermented by the resident bacteria to these acids; therefore, they contribute VFA for epithelial development. Plastic sponges and inert particles - both added to the rumen to provide “scratch” - did not promote development of the epithelium. These objects could not be fermented to VFA, and thus did not contribute any VFA to the rumen environment. Therefore, rumen development (defined as the development of the epithelium) is primarily controlled by **chemical**, not **physical** means.

Availability of Substrate. Bacteria, liquid, rumen motility, and absorptive ability are established prior to rumen development, or develop rapidly when the calf begins to consume dry feed. Thus, the primary factor determining ruminal development is dry feed intake. To promote early rumen development and allow early weaning, the key factor is early consumption of a diet to promote growth of the ruminal epithelium and ruminal motility. Because grains provide *fermentable carbohydrates* that are fermented to propionate and butyrate, they are a good choice to ensure early rumen development. On the other hand, the structural carbohydrate of forages tend to be fermented to a greater extent to acetate, which is less stimulatory to ruminal development.

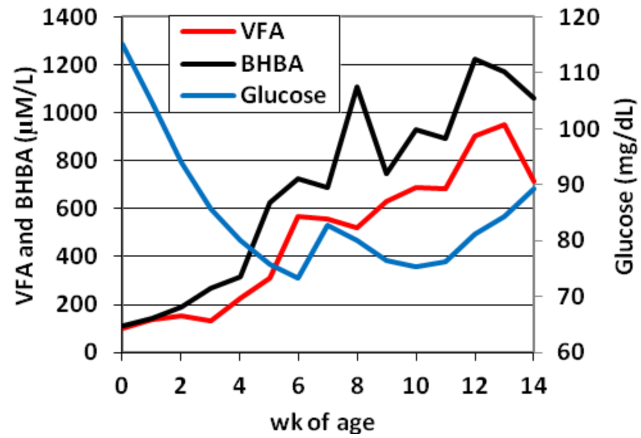

Figure 7. Changes in concentration of blood metabolites in response to weaning. From: Quigley et al., 1991a, 1991b.

Changes in Nutrients with Dry Feed Intake

As the rumen develops, there is a change in the types and amounts of nutrients available to the calf. For example, the amount of glucose available from intestinal digestion of lactose from milk or milk replacer is replaced by VFA from ruminal fermentation. Consequently, the amount of glucose in the blood declines and the amount of VFA and ß-hydroxybutyrate increase (Figure 7). Since glucose is the major energy metabolite, decreased availability of glucose requires a considerable shift in "metabolic machinery" by the calf.

Effect of Physical Form of the Ration

The role of forage. For many years, producers have fed forage - primarily hay - to calves to promote ruminal development. The common reason was to give the calf the "scratch" needed to start development of the rumen. The effects of intake of forage vs. starter can be seen clearly in Figures 8 and 9. Figure 8 shows the stomach of a six week old calf consuming milk plus starter and Figure 9 shows the stomach of a six week old calf consuming milk plus forage. Note the difference in size of the reticulorumen of the stomach of the calf that consumed starter.

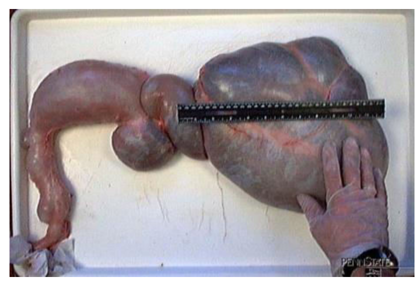

Figure 8. Stomach of 6 week old calf consuming milk plus starter. Source: Penn State Univ.

In fact, the development of rumen function is primarily chemical and is caused by production of VFA in the rumen. Providing forage has less of an effect on ruminal epithelial development, thus on activity and function. The concept of "scratch" to develop the rumen is a myth. However, forage *is important* to promote the growth of the muscular layer of the rumen and to maintain the health of the epithelium. Rumen papillae can grow too rapidly in response to high levels of VFA - when this happens, they may clump together, reducing the surface area available for absorption. Also, some "scratch" *is* needed to keep the papillae free of layers of keratin, which can also inhibit VFA absorption. Therefore, hay should be part of the diet, but *after* weaning.

Another reason not to feed hay to calves prior to weaning is the energy requirement of young calves. Calves have a high energy requirement relative to their ability to consume dry

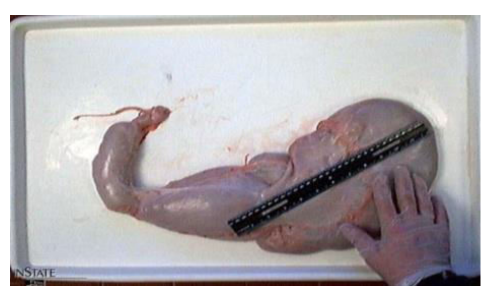

Figure 9. Stomach of 6 week old calf consuming milk and hay. Source: Penn State Univ.

feed. Therefore, if calves consume significant amounts of hay, their intake of other feeds (i.e., starter) will be limited. This has the effect of reducing intake of starter, which can slow growth. Finally, most hay has too little energy for calves. The energy requirement for calves can usually be met only when calves are fed milk or high quality milk replacer, and/or excess colostrum and calf starter. Even good quality legume hay generally has too little energy to support growth of preweaned calves.

Calf Starters

Traditional calf starter feeds in most parts of the world rely on corn, soybean meal and oats or barley as primary ingredients. Starters may be ground (meal) form, pelleted or texturized (Figure 10). Many companies add molasses as a palatability agent to promote early feed intake and minimize fines (small particles from pellets and grains) and vitamins, minerals and selected additives.

Figure 10. High quality calf starter containing processed corn.

Calves may transition to a grower feed sometime after weaning, depending on the management on the farm. Typically, producers continue to feed the starter feed after calves are weaned and moved from individual housing into groups. This reduces one stress on the calves (change in feed) for at least 10 days. Thereafter, forage will be added to the diet, followed by the transition to a grower or total mixed ration. On larger farms, heifers are grouped by age or size and individual total mixed rations are formulated for each group (Figure 11).

Nutrients in starters. Calf starters are unique feeds on the farm. They are formulated to be highly digestible, palatable and stimulate early feed intake and rumen development. They are often the most expensive feeds used on the farm. Starters and growers should contain nutrients as outlined in Table 3 (NRC, 2001).

It should be noted that calves fed accelerated milk replacer formulations often are fed higher protein (20% of DM) starters to maintain growth after weaning.

Figure 11. Weaned heifers in groups fed calf grower plus forage.

Ingredient selection. Simple calf starters can be formulated using corn, soybean meal and oats (Table 4). However, due to the high ingredient cost, the effect of replacing corn and soybean meal has been the subject of extensive research. Lower cost by-product ingredients such as cottonseed and soybean hulls, sugar beet pulp, processed alfalfa and other ingredients have been evaluated. For example, Maiga et al. (1994) reported lower ADG when calves were fed diets containing 20% alfalfa from birth to 12 wk of age. Williams et al. (1987) fed calves diets with barley or a citrus and beet pulp combination, but feed efficiency was greater when barley was fed. In a similar second study, Williams et al. (1987) fed calves barley or beet pulp and reported DM and N digestion to be lower in calves fed beet pulp. Many other similar studies exist in the literature; generally, successful use of by-products depends on high digestibility of the ingredient, palatability, and amount of readily fermentable carbohydrate and fiber it contains. Excess fermentation or excess fiber will reduce intake and growth.

The amount of starch and form of starch in a formula has a critical effect on rate of rumen fermentation, rumen pH, VFA production and animal performance. Assume that a formula contains 12% water, 20% crude protein, 4% fat, and 8% ash. This leaves 56% of the formula as carbohydrate. This may be partitioned among sugars, starch and fiber fractions. There is tremendous variability in carbohydrate fractions in commercial calf starters. And selection of the type of starch may affect rumen fermentation and VFA production.

Item, DM basis	Starter	Grower
Crude protein, %	18.0	16.0
ME, MJ/kg	13.7	13.6
NDF, %	12.8	18.0
Ca, %	0.7	0.6
P, %	0.45	0.40

Table 3. Recommended composition of calf starter and grower. Source: NRC, 2001.

Laarman et al. (2012) reported minimal effect of varying starch concentrations on rumen pH or severity of rumen acidosis. However, in this study, dietary starch only varied from 31 to 35% and all diets were pelleted. This difference in dietary starch was likely insufficient to measure differences in the variables measured. Khan et al. (2007) reported that intake and growth from 1 to 84 days was greater when calves were fed starters containing 25% starch from corn compared to 25% starch from barley, oats or wheat. Feed efficiency was greatest when corn or wheat were fed.

Physical form of starter. A traditional requirement for calf starters for appropriate rumen development (particularly long-term rumen development) has been the inclusion of some form of effective fiber to physically remove keratin from ruminal papillae and maintain proper VFA absorption. This is particularly true when forage is not included in the diet prior to weaning. This requirement was most clearly identified by the work of McGavin and Morrill (1976) who showed excessive keratinization of ruminal papillae in calves fed diets with insufficient effective fiber. Greenwood et al. (1997) proposed a minimal amount of effective fiber and a method for determining the amount of fiber in starter rations.

Ingredient	%
Corn, cracked	52.0
Soybean meal	20.0
Oats, rolled	20.0
Molasses, liquid	5.0
Animal fat	1.50
Limestone	1.0
Dicalcium phosphate	0.25
Salt, trace mineral	0.20
Vitamin premix	0.05
Total	100.00

Table 4. Example of a simple calf starter formula.

Franklin et al. (2003) evaluated physical form of calf starter and determined that calves fed textured starter consumed more starter and grow faster than calves fed pelleted or ground starters. In this study, the textured starters contained 27% cracked corn, 13% oats and pellets composed of wheat middlings and corn gluten meal. The pelleted and ground starters contained different ingredients and were primarily corn, oats, and either soybean meal (ground) or wheat middlings and corn gluten meal. This study confirms the general observation in the industry that textured starters are generally most palatable and promote intake. However, the difference between textured and pelleted starters in this study were greater than other studies and may be related to ingredient selection as well as form of the starters.

Porter et al. (2007) also showed that a coarse mashed starter formation improved digestion of DM, TDN, crude fiber and NDF compared to a completely pelleted starter (Figure 12), suggesting that form of the starter was important to optimal rumen development, particularly when calves have neither forage in the diet nor bedding to consume. It should be noted that other researchers have reported little difference between textured or pelleted starters (Warner et al., 1973); however, these diets were fed in the presence of either forage or bedding, which can alter fermentation dynamics.

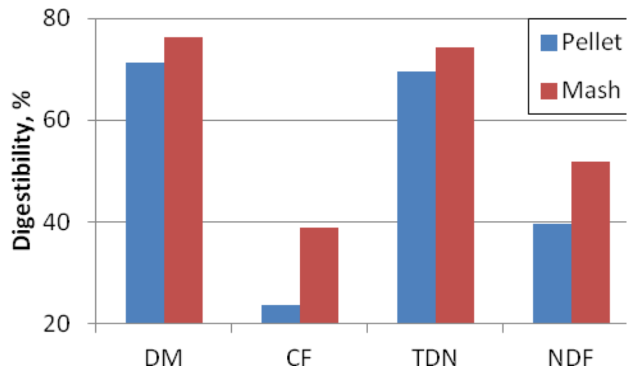

Figure 12. Digestibility of dry matter (DM), crude fiber (CF), total digestible nutrients (TDN) and neutral detergent fiber (NDF) in calves fed starters of different forms. All treatments differ, $P < 0.01$. Source: Porter et al., 2007.

Hill et al. (2008) found that replacing corn in calf starters with molasses (up to 10%) or soybean hulls (14-63%) reduced intake and daily gain; however, feeding whole oats (25%) supported excellent intake and growth.

Processing. Research conducted at Pennsylvania State University has evaluated the form of corn in texturized calf starters (Lesmeister and Heinrichs, 2004). Corn was processed – either whole, dry rolled, roasted rolled or steam flaked – and added to a pellet and whole oats to make the calf starter. Calves (n = 92) were fed one of the starters for 42 days. The form of corn had significant effects on intake, growth and rumen development. Interestingly, the steam flaked corn (which is the most common type of corn used in textured feeds in the U.S.) promoted excessive papillae development, greater amounts of volatile fatty acids in the rumen and blood, and lower starter intake and growth. This may be because the steam flaking resulted in corn that was very light and fluffy and increased the rate of fermentation in the rumen. This effectively increased production of rumen propionate and butyrate. Calves consuming whole corn or roasted rolled corn (which was fermented less rapidly in the rumen) ate the most calf starter and had best gains.
Jarrah et al. (2013) reported that processing barley as either coarse ground, whole, steam-rolled or roasted had no effect on growth, intake or efficiency to 56 days of age. These authors concluded that whole barley was equally effective as other, more expensive, sources.

Suarez-Mena et al. (2015) concluded that whole oats fed with pellets or ground oats included in the pellet had marginal effects on rumen pH and rumen development. However, the diets were only fed for 3-4 weeks only and the unground whole oat diet was only 25% inclusion. The authors hypothesized that this inclusion rate may have been too small to alter the texture of the diet to influence rumen parameters. Further, the high starch level of the diets (43-44% of DM) may have overshadowed any differences in form.

Additives and molasses. Many additives are added to calf starters to promote intake, maintain pellet integrity, improve palatability or influence calf health. For example, Lesmeister et al. (2004) showed that addition of yeast culture to the calf starter increased intake of starter, body weight gains and indices of rumen development when fed to calves at 1 or 2% of the formula to 42 days of age. Starter intake was increased by nearly 70% when yeast culture was included in the diet at 2% of the formula. Yeast culture improves rumen development by promoting growth of ruminal bacteria and controlling production of lactate in the rumen (Quigley et al., 1992b). Calves often produce excess lactate due to relatively low production of saliva, low amounts of bicarbonate in saliva, and lack of regurgitation. Other studies have not shown a similar effect (e.g., Hill et al., 2009), so caution is required in interpreting effects of specific additives on animal performance.

Item	Percent Molasses in Starter	
	5%	12%
BW, kg		
Initial	43.1	43.3
Final	53.3	51.8
ADG, g/d		
Week 1 to 4	357	327
Week 5 to 6	628	512
Week 1 to 6	449[c]	389[d]
CMR intake, g/d	536	539
Starter intake, g/d		
Week 1 to 4	139	107
Week 5 to 6	1130[a]	960[b]
Week 1 to 6	509[a]	396[b]
Gain: feed, g/kg		
Week 1 to 4	455	435
Week 5 to 6	483	448
Week 1 to 6	495	463

Table 5. Performance of calves fed textured starter with 5 or 12% molasses.
[a,b]Means with different superscripts differ, $P < 0.05$.
[c,d]Means with different superscripts differ $P < 0.15$
Source: Lesmeister et al., 2005.

An additional study (Lesmeister and Heinrichs, 2005) fed calf starters containing different amounts of liquid molasses (74% DM, 4.7% protein, 60.6% sugars as invert sugars, 12.2% ash). The starter was a commercial textured starter that contained 5% molasses; the experimental treatment was produced by adding the additional molasses to the starter. Holstein calves (n = 46) were used in the study, beginning at 2 days of age. Calves were fed colostrum prior to starting the study. Adding molasses to starter tended to reduce body weight gain and reduced starter intake during the last two weeks of the trial (Table 4). Overall starter intake (weeks 1 to 4) was also reduced significantly. Calves fed 12% molasses ate 22% less starter than calves fed starter containing 5% molasses. *Fines.* Presence of fines can reduce starter intake and delay weaning. For example, the commercial starter in Figure 13 contains a large proportion of fines that can reduce intake, particularly in very young calves (BAMN, 20003). Bateman et al. (2009) showed clearly that increased amounts of fines (geometric mean of particle size was reduced from 2.03 mm to 0.81 mm by addition of ground feed to the starter) in a starter reduced intake by about 10%. Intake was reduced by 11% and BW gain was reduced by 8% from d 29 to 56 (post-weaning).

Klein et al. (1987) reported very early starter intake in calves fed a prestarter containing milk proteins and added to the milk bucket near the end of milk feeding. Such a system promoted early intake of solid feed with earlier rumen development. These researchers successfully weaned calves as early as 17 days of age without effect on post-weaning growth or health.

Forage inclusion. Coverdale et al. (2004) reported that the addition of 7.5 or 15% forage (bromegrass hay) to textured starter diets increased growth and feed efficiency in Holstein calves (n = 60). Both starters and hay contained 21 to 23% CP. Forage was mixed with starter to ensure equal intake of both ingredients. Starters were composed primarily of corn, wheat middlings, soybean meal and a small amount of soy hulls and oats (whole or ground). Although research results indicating the value of inclusion of forage are somewhat equivocal, these data suggest that greater attention should be paid to formulation of diets – particularly as it is related to carbohydrate fermentability, rumen development and rumen health after weaning.

Figure 13. Calf starter containing a high proportion of fines. This starter will be poorly consumed by young calves.

Several trials have shown improved performance when calves are fed forage (Castells et al., 2012, 2013; Daneshvar et al., 2015; EbnAli et al., 2016; Khan et al. 2011; Montoro et al., 2013; Coverdale et al., 2004; Beiranvand et al., 2014; Terré et al., 2013, 2015). Laarman and Oba (2011) and Laarman et al. (2012) reported that including forage in the diet increased rumen pH and reduced the amount of time that calves experienced acidosis (rumen pH < 5.8). Kim et al. (2016) reported similar findings using ruminally cannulated calves. Quigley et al., 1992b also reported that including forage in the ration influenced several measures of rumen fermentation post-feeding. Daneshvar et al. (2015) concluded that final BW, starter intake, total DMI and ADG were greater ($P < 0.01$) in forage-supplemented calves than those that received no forage during the preweaning, postweaning, and overall periods (Table 6).

Other researchers have reported reduced performance, (Hill et al., 2008, 2009, and 2010) and others have reported no difference in performance (Jahani-Moghadam et al., 2015; Mirzaei et al., 2015). Stobo et al. (1966) fed calves weaned at 5 weeks of age 90 and 33% concentrate diets. Digestibility of crude fiber was 18.4% and 57.3% at 13 wk for calves fed 90% and 33% concentrate, respectively, and 14.5 and 54.0% digestible at 17 wk, respectively. It appears that high concentrate diets may impair digestion of fiber in the rumen, probably by maintaining pH lower than optimal for rumen cellulolytic bacteria.

Item	F+	F-	*P*
Final BW, kg	92.5	83.1	0.01
Starter intake, kg/d	0.90	0.65	0.01
Total DMI, kg/d	1.43	1.17	0.01
ADG, kg/d	0.73	0.60	0.01

Table 6. Performance of calves fed diets without (F-) or with (F+) forage. From Daneshvar et al. (2015).

Imani et al. (2016) conducted a meta-analysis of published trials to evaluate the effect of forage provision on growth and rumen fermentation of calves. Studies (n = 27) from 1998 to 2016 were used. The authors concluded that intake of starter, BW gain, rumen pH and ruminal acetate concentration increased when forage was supplement. On the other hand, feed efficiency was reduced. The possibility that at least some of the difference in BW and BW gain were due to gut fill were noted. There was also an interaction of forage inclusion on starter form -- including forage to texturized feeds had less effect on growth compared to including forage to pelleted feeds. Forage would conceivably reduce post-prandial drop in rumen pH and the risk for ruminal acidosis. This is especially true when animals are limit fed starter with ad lib forage (Quigley et al., 1998). Lower energy content of forage compared to concentrate suggests that forage should be limited to ≤5% of DM to minimize effects on energy intake and minimize depression of intake due to gut fill.

Because texturized calf starters commonly contain less fiber (ADF, NDF) than pelleted starters, the inclusion of forage would have less effect on ruminal NDF digestion. Conversely, if a pelleted feed contained significant NDF, then including forage could help maintain adequate ruminal fiber digestion and support higher NDF digestibility. Terré et al (2013) recommended that a low NDF, pelleted starter was recommended (compared to a high NDF pelleted starter) and inclusion of chopped hay immediately after weaning was recommended.

Hosseini et al. (2016) offered calves no alfalfa hay or 15% of the ration DM beginning at 2, 4, or 6 wk of age. Calves were fed milk at 10% of BW and a ground calf starter containing 62% barley. The authors reported that performance from birth to 73 d of age was greatest when calves were offered alfalfa hay at 2 wk of age.

Summary

Rumen development of calves is critically important to ensure adequate, consistent growth. Development of the rumen occurs when calves begin consuming fermentable carbohydrates from calf starter. Production of VFA stimulates physical and metabolic development of the rumen and peripheral tissues to prepare the calf for weaning.

Proper ingredient selection to provide required nutrients in a form that are palatable and maintain normal rumen function is essential. Forage should not be offered until rumen development has commenced. Thereafter, forage is important to minimize the risk of rumen acidosis and development of parakeratosis.

On farm management to optimize early starter intake – availability of starter and water, proper timing of forage introduction into the ration, etc. – can markedly ease transition from monogastric to ruminant and improve profitability for the producer.

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