Modeling the Effects of Liquid Intake and Weaning on Digestibility of Nutrients in Pre- and Post-Weaned Dairy Calves

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Introduction

Accurate predictions of nutrient supply and nutrient requirements are essential to modern ration formulations and animal production. Accurate and precise models allow provision of nutrients to meet requirements for maintenance and optimal production without supplying excess nutrients that contribute to inefficiency or environmental damage.

Most nutrient models predict supply of metabolizable energy (**ME**) and metabolizable protein (**MP**); in lactation models, flow of nutrients are predicted from endogenous, microbial, and undegraded dietary sources. Nutrient requirements are usually predicted using factorial calculation of requirements for maintenance (adjusted for environmental and management considerations), growth, pregnancy, and lactation. Only maintenance and growth predictions are used to predict nutrient requirements for calves, with requirements for pregnancy included for primiparous heifers.

For young calves and heifers, prediction of nutrient supply by the 2001 Nutrient Requirements of Dairy Cattle (NRC, 2001) assumes fixed digestibility and metabolizability of energy and protein. For example, calculation of ME from milk replacer is assumed to be the caloric content of protein, fat, and lactose adjusted for digestibility and metabolizability:

ME (Mcal/kg) = [(0.057 x CP) + (0.092 x EE) + (0.0395 x CHO)] x 97% x 96%, where:

CP = crude protein %, EE = ether extract %, CHO = carbohydrate %, 97% = digestibility of nutrients, and 96% = metabolizability of digested nutrients.

Metabolizable energy content of calf starters is calculated as the sum of the digestible fractions of protein, non-fiber carbohydrates, neutral detergent fiber (**NDF**), crude protein (**CP**), and fat as described in the 2001 Dairy NRC (NRC, 2001) for adult cattle. Neither liquid nor starter feeds are corrected for differences in digestibility caused by age or development of the gastrointestinal tract in these models.

In young calves, digestibility of dry feeds (concentrates and forages) depends on development of ruminal fermentation and intestinal digestion. This is particularly true for NDF (primarily fermented in the rumen) and starch (dependent on ruminal fermentation and small intestinal digestion). Studies have shown that fiber fermentation is limited in neonatal calves (Chapman et al., 2016; Hill et al., 2016a, b). Further, pancreatic α-amylase production is low at birth (Siddons, 1968) but increases with age (Huber et al., 1961; Morrill et al., 1970) along with total pancreatic secretion (McCormick and Stewart, 1966), thereby affecting small intestinal digestion of starch (Morrill et al., 1970).

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Development of microbial fermentation changes flow of nutrients from the stomach. Prior to weaning, nutrients are derived primarily from milk protein, fat, and lactose; after weaning, nutrients are provided by volatile fatty acids absorbed from the rumen and microbial protein that increases in flow with increasing dry feed intake (Leibholz, 1975; Quigley et al., 1985).

Changing amounts and types of liquid fed to calves may alter age at which dry feed intake begins (Strzetelski et al., 2001; Hill et al., 2006a,b) thereby altering rumen development. This is particularly true when large amounts of liquid are fed (i.e., greater than about 700 g/day of solids from liquid for Holstein calves), since large amounts of liquid consumed will delay rumen development (Terré, et al., 2007). Several studies have reported increased BW at weaning for calves fed large amounts of liquid pre-weaning; however, the advantage in growth compared to conventional feeding methods (500 to 700 g/day of solids) may be lost as BW gain slows dramatically in the period immediately post-weaning. We have attempted to quantify the effects of increased milk replacer allowance on digestibility of starter and its effects on growth and efficiency of young calves to determine if differences in digestion of nutrients, but particularly of carbohydrates, which may be at least partially responsible for differences in growth.

Digestion of Solid Feed

Calves are commonly weaned between 1 and 3 months of age in most dairy systems, with the most common age being approximately 9 weeks of age in the U.S. (USDA, 2016). Weaning to dry feed requires that the calf has sufficient digestive and fermentative capability to provide nutrients to support maintenance and growth. Further, the source of nutrients changes from milk digested primarily in the small intestine to grain-based ingredients fermented in the rumen and (or) digested in the small intestine. Therefore, gastrointestinal, hepatic, and systemic enzyme systems must be sufficiently adapted to changing sources of nutrients. If a calf is inadequately prepared for weaning, performance may suffer and predispose calves to reduced growth, poor efficiency, and even increased susceptibility to disease (Roth et al., 2008, 2009).

The most important factor in promoting rumen development and adaptation in preparation for weaning is consumption of dry feed containing fermentable carbohydrates – particularly sugars and starch – that are fermented to propionate and butyrate in the rumen by resident rumen bacteria. Production of volatile fatty acids and microbial protein stimulate a series of adaptations in the rumen, gastrointestinal tract, hepatic tissues, and systemically that promote gluconeogenesis, production, and release of β-hydroxybutyrate by rumen epithelium and utilization of acetate by peripheral tissues (Howarth et al., 1968; Huber, 1969; Baldwin et al., 2004).

In the past 15 years, some dairy experts have recommended feeding milk or milk replacer in excess of the traditional recommendations (approximately 10% of body weight as milk or reconstituted milk replacer) to increase rate of gain and take advantage of improved calf efficiency (Diaz et al., 2001; Moallem et al., 2010; Davis-Rincker et al., 2011). High digestibility and metabolizability of liquid feeds compared to higher fiber ingredients in calf starters naturally contributes to greater efficiency of BW gain.

Calves fed whole milk for *ad libitum* consumption or milk replacer to amounts >1 kg/day of powder gain impressive amounts of BW. For example, Jasper and Weary (2002) reported that calves fed milk for *ad libitum* consumption were 8 kg heavier at the end of a 63-day feeding period compared to calves fed milk at 10% of BW. All calves were weaned at 42 days. However, daily BW gains in calves fed for *ad libitum* consumption were markedly lower during the week of weaning (0.36 vs. 0.53 kg) and after weaning (0.68 vs. 0.85 kg), so that BW differences at 63 days were not as great as the difference prior to weaning.

Differences in growth rate post-weaning in calves fed differently pre-weaning may be due to differences in gastrointestinal development and digestion. Several recent studies indicate that digestion of nutrients from dry feeds varies when calves are fed varying amounts of liquid pre-weaning.

Terré et al. (2007) fed Holstein bull calves (19 days of age at start of the trial) milk replacer (**MR**) at levels typical of conventional feeding (CF; 4 L/day with weaning at 35 days of the study) or an enhanced feeding (**EF**) program wherein amount of MR was increased to 7 L/day and then reduced to weaning.

Total starter intake on the CF and EF programs prior to weaning were 23.8 and 12.6 kg, respectively. Results of a digestion trial conducted during days 38 to 42 of the study are in Table 1. These data indicate clearly that digestion of dry feed was impaired in calves fed EF, likely due to inadequate rumen development as a result of lower starter intake.

Digestion of NDF (derived primarily from wheat middlings, soybean hulls, and wheat distiller's grains) in the study by Terré et al. (2007) was lower in EF calves compared to CF calves (20.3 vs. 34.7%; Table 1). Since disappearance of NDF is due primarily to ruminal fermentation, it is likely that reduced NDF digestion was due to inadequate or incomplete rumen fermentation in EF calves. Reduced NDF digestibility occurred in EF calves in spite of a higher rumen pH (5.73 vs. 5.99). Ruminal pH less than approximately 6.0 is associated with impaired ruminal fiber fermentation (Shriver et al., 1986; Allen, 1997) due to pH sensitivity of cellulolytic bacteria in the rumen (Hoover, 1986; Russell and Wilson, 1996). In the study by Terré et al. (2007), the authors attributed higher ruminal pH to lower ruminal activity due to lower starter intake and a lack of substrate available for fermentation.

Leibholz (1975) monitored digestion of nutrients in calves fed whole milk or MR to weaning at 35 days of age. After weaning, calves were offered a pelleted feed consisting of 58% barley, 20% soybean meal, 15% wheat straw, and 3% molasses plus vitamins and minerals. The diet contained 15% protein and 13% ADF; we estimated the diet contained 2.7 Mcal of ME/kg and 50% non-fiber carbohydrate.

By 6 weeks of age (1 week post-weaning), digestibility of ADF reached 57% and did not change markedly thereafter. However, the site of ADF digestion changed dramatically with time after weaning as most ADF was digested in the hindgut during the first 4 wk of the trial (Figure 1).

Weekly DMI for each week of the 8 week study were 0.6, 1.1, 1.5, 2.1, 2.2, 2.4, 2.5 and 2.5 kg/day. Intake of ADF ranged from 77 g/day in the 1st week post-weaning to 325 g/day at week 8. Therefore, it is possible that higher digestion of ADF in the hindgut during the first few weeks after weaning was due to small amounts of ADF consumed.

Hill et al. (2010) fed calves (2 to 3 days of age at start of study) 1 of 4 MR programs: 0.44 kg/day of DM of a 21% CP, 21% fat MR powder for 42 days (A); 0.66 kg/day of DM of a 27% CP, 17% fat MR powder for 42 days (B); 0.66 kg/day of DM of a 27% CP, 17% fat MR powder for 28 days (C); or up to 1.09 kg/day of DM of a 29% CP, 21% fat MR for 49 days (D). Digestibility estimates were made on days 53 to 56. Table 2 shows clearly that digestion of dry matter (**DM**) and organic matter (**OM**) were lower when calves were fed large amounts of MR prior to weaning (treatment D). During the digestibility period (days 53 to 56), intake of starter DM was 2.2, 2.3, 2.5 and 1.9 kg/day for treatments A, B, C, and D, respectively. The trend ($P < 0.08$) for low starter DM intake, coupled with significantly lower digestion of DM, resulted in calves on treatment D only consuming about 71% of the digestible DM of calves on the other treatments.

More recently, Chapman et al. (2016) reported that digestion of nutrients, but particularly of NDF and ADF, were reduced during the digestion period of days 52 to 58 of age when calves were fed MR up to 0.87 kg/day (Table 3). Although digestion of all nutrients (except starch) were reduced significantly, digestion of NDF and ADF were reduced nearly 50% in calves fed large amounts of milk pre-weaning.

Conversely, Chapman et al. (2017) reported no difference in NDF digestion when calves were fed MR at 446, 669, or 892 g/day of MR during the digestibility measurement period. Further, NDF digestion was 58, 69, and 69%, respectively, suggesting extensive digestion of fiber by the calves. However, the starter used in the study contained only 16% NDF and starter intake during the trial was 1.1, 0.7 and 0.4 kg/day, respectively. Measurements were taken prior to weaning, which may have increased the error associated with measurement.

A majority of these data suggest that calves fed large amounts of milk pre-weaning may have difficulty digesting nutrients from dry feed during the immediate post-weaning period. There are numerous implications to these findings. For example, digestion of starters containing greater amounts of fibrous by-products may be difficult if calves are fed large amounts of liquid pre-weaning. Also, it may be necessary to use increasingly complex liquid reduction strategies to ensure that starter intake (and digestibility) is adequate prior to weaning.

Because fiber digestion is primarily influenced by cellulolytic fermentation in the rumen, the low digestibilities of ADF and NDF (Table 3) indicate that the rumen is less well developed in calves fed greater amounts of MR (Chapman et al., 2016). Also, fiber digesting microorganisms are established in the rumen more slowly than starch and sugar digesting microorganisms (Anderson et al., 1987). Finally, selection of ingredients that may negatively affect rumen fermentation (e.g., inclusion of oil-containing ingredients) may also reduce total DM digestion (Hill et al., 2015).

To better understand the changes in NDF digestion with age and diet, Hill et al. (2016b) fed calves a moderate or aggressive MR feeding program and monitored changes in nutrient digestion with advancing age. Figure 2 shows changes in NDF digestion with advancing age. The effect of diet is clearly shown, as calves fed more milk (AGG in Figure 2) maintained lower NDF digestion throughout the 3 digestibility periods. Also, calves fed functional fatty acids and nutrients (NeoTec5g®, Provimi North America, Brookville, OH, USA) feed additive (MOD+ and AGG+ in Figure 2) had higher NDF digestion in periods 2 (42 to 46 days of age) and 3 (54 to 58 days of age). Previous studies (Guilloteau et al., 2009, 2010; Hill et al. 2007) have shown that feeding sodium butyrate (a component of NeoTec5g) improved fiber digestion in young calves.

Calves fed the moderate MR program (MOD in Figure 2) consumed more starter throughout the trial, which likely hastened rumen development and the ability of calves to digest NDF. In calves fed MOD, NDF digestion increased from approximately 15% at 19 to 23 days of age to approximately 35% by 51 to 56 days of age. Digestion of NDF in calves fed the higher level of MR (**AGG**) did not change markedly through the 56-day study, and there were few differences with advancing age.

In addition to age of calf, digestion of nutrients post-weaning is affected by ingredient source and form of calf starter. Digestion of DM, OM, and CP were higher in starters containing ground corn, whereas ADF and NDF digestion were greatest in starters containing soybean hulls (Table 4). Hill et al. (2016a) also reported that texturized calf starters containing whole corn and whole oats (51 to 54% starch and 13% NDF) had higher DM, OM, and CP digestibilities than pelleted starters containing wheat middlings, soybean hulls, and dried distiller's grains (20% starch and 36% NDF; Table 5). On the other hand, pelleted, high-fiber starters had higher ADF, NDF, starch, and fat digestion. Gain of BW and hip width increased as OM digestibility increased in these trials.

Collectively, these data suggest that the availability of energy from starters is dependent on type of carbohydrate, form of the starter (texturized vs. pelleted) and carbohydrate, age of the calf, and intake of liquid pre-weaning.

Current nutrient models for calves and heifers (e.g., 2001 Dairy NRC) ignore the effects of previous nutrition and extent of rumen development. The ME content of starters is a static calculation based on expected digestibility of nutrient fractions (NDF, non-fiber carbohydrate, protein, and fat). No provision is made for differing nutrient digestibilities with advancing age or intake. Conversely, other models for lactating cows utilize dynamic calculations of energy based on rates of ruminal digestion of each fraction (NFC, NDF, protein, and fat) and rate of passage (Higgs et al., 2015). Intestinal digestibility coefficients are then applied to the ruminally undegraded fraction to estimate total nutrient supply.

Using data from Chapman et al. (2016) and Hill et al. (2016b), we estimated ME concentrate of calf starter using the method outlined in the 2001 NRC Nutrient Requirements of Dairy Cattle (NRC, 2001), as well as calculated ME based on analyzed values using digestibility data from Table 3 and Figure 2. Results are in Table 6. The column labeled "NRC" contains calculated ME concentration in starter based on the 2001 NRC method, assuming digestibility values typical for adult ruminants. The column "Calculated" contains data using total tract digestibility measured in the studies by Chapman et al. (2016) and Hill et al. (2016b). We also used the 2001 Dairy NRC model to predict ME-allowable BW gain using the ME values calculated for calf starter using the NRC or calculated values in Table 6.

Differences were significant for all measurements, but ME was markedly overestimated in calves fed higher levels of milk in both studies. Consequently, predicted ME-allowable gains using the calculated ME value for calf starter were lower compared to predicted gains using the ME values calculated with the NRC calculations.

The implications of errors in calculation of ME content are clear, as calves fed high levels of milk pre-weaning will be ill prepared for weaning and will be unable to extract nutrients from calf starters efficiently. Consequently, growth of calves will be compromised until sufficient maturation of the digestive tract and associated tissues allows the calf to fully utilize nutrients in the calf starter. The existing NRC model over-predicts ME supply from starters by 12 to 26% (Table 6).

These data also suggest that additional time may be needed for a weaning transition to ensure that calves fed high levels of milk will consume sufficient starter prior to weaning. In most of the studies cited in this review, liquid intake was reduced for 7 to 10 days prior to weaning. For calves fed 1 kg/day of powder or greater, this is probably insufficient time for adaptation.

Summary

The 2001 Dairy NRC represented an important improvement in our understanding of nutrient requirements for young calves and heifers. Further refinement of methods to estimate nutrient supply of young calves will improve our ability to calculate growth under a wide range of feeding and management conditions.

Feeding varying amounts of liquid from milk or MR has important implications to growth post-weaning. Increasing liquid consumption above approximately 650 to 700 g/day of solids will delay initiation of calf starter intake and will delay onset of rumen development. Digestion of all nutrients, but particularly NDF, is essential to ensure that rumen development is adequate prior to weaning.

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Table 1. Apparent total tract digestibility of dry feed in calves fed 4 L/day of milk replacer (**MR**) at 12.5% DM dilution rate from day 1 to 28, and 2 L/day from day 29 to day 35 (**CF**) or MR at 18% DM dilution rate: 4 L/day from days 1 to 6, 6 L/day from days 7 to 13, 7 L/day from days 14 to 20, 6 L/day from days 21 to 28, and 3 L/day from days 29 to 35 (**EF**). Digestibility was measured the week after weaning. Adapted from Terré et al. (2007).

Digestibility, %	CF	EF	SE	P
Dry matter	77.4	71.8	1.23	0.01
Organic matter	78.7	73.2	1.18	0.01
Crude protein	77.1	71.6	1.29	0.01
Neutral detergent fiber	34.7	20.3	3.79	0.02
Gross energy	75.6	69.8	1.25	0.01

Table 2. Total tract apparent digestion of dry matter (**DM**), organic matter (**OM**), crude protein (**CP**), and fat in calves fed 1 of 4 MR programs: 0.44 kg/day of DM of a 21% CP, 21% fat MR powder fed for 42 days (A); 0.66 kg/day of DM of a 27% CP, 17% fat MR powder fed for 42 days (B); 0.66 kg/day of DM of a 27% CP, 17% fat MR powder fed for 28 days (C); or up to 1.09 kg/day of DM of a 29% CP, 21% fat MR fed for 49 days (D). Adapted from Hill et al., 2010.

Digestion, %	A	B	C	D	SE	P
DM	75.6[a]	78.3[a]	78.7[a]	67.3[b]	2.19	0.01
OM	77.4[a]	78.3[a]	78.7[a]	68.0[b]	2.20	0.01
CP	72.4	72.3	74.1	71.8	2.58	0.83
Fat	70.3	75.4	76.3	75.4	3.37	0.33

[a,b]Means in the same row with different superscripts differ, P < 0.05.

Table 3. Body weight (**BW**), DM intake (**DMI**), and total tract digestibility of nutrients in calves fed conventional [CON; 0.44 kg of dry matter (**DM**), 21% crude protein (**CP**), 21% fat powder fed for 42 days], moderate (MOD; 0.66 kg of DM, 27% CP, 17% fat powder fed for 42 days), and aggressive program (AGG; up to 0.87 kg of DM, 27% CP, 17% fat powder fed for 49 days). Digestibility was measured from days 51 to 56. From Chapman et al., 2016.

Item	CON	MOD	AGG	SE	P
BW, kg	62.7[a]	72.3[b]	82.8[c]	4.05	0.01
DMI, kg/day	2.04	2.30	2.28	0.258	0.08
Digestibility, %					
DM	77.6[a]	76.9[a]	66.0[b]	1.67	0.01
OM	79.2[a]	78.2[a]	67.9[b]	1.65	0.01
ADF	56.3[a]	53.2[a]	26.7[b]	3.89	0.01
NDF	54.1[a]	50.7[a]	26.2[b]	2.86	0.01
Starch	96.7	94.5	94.0	1.33	0.36
CP	71.9[a]	74.1[a]	56.3[b]	2.72	0.02
Sugar	93.1[a]	91.5[a]	86.2[b]	1.68	0.02
Fat	81.4[a]	83.2[a]	74.1[b]	1.84	0.01

[a,b,c]Means in the same row with different superscripts differ, $P < 0.05$.

Table 4. Nutrient digestibility in calves 15 to 16 weeks of age fed starters containing soybean hulls (**S**), wheat middlings (**M**), or corn (**C**). Contrast 1 = (S+M) vs. C; and contrast 2 = S vs. M. Adapted from Hill et al., 2016a.

Digestibility, %	S	M	C	SE	Contrast 1	Contrast 2
DM	76.9	78.9	85.2	1.58	0.01	0.23
OM	77.5	79.6	85.8	1.56	0.01	0.21
ADF	65.5	53.5	55.4	3.48	0.20	0.01
NDF	70.7	56.1	66.2	3.13	0.34	0.01
Starch	97.6	98.9	97.0	0.57	0.13	0.15
CP	78.1	80.7	84.4	1.75	0.01	0.16
Sugar	94.2	95.6	94.2	1.79	0.63	0.47
Fat	84.1	86.3	89.6	2.61	0.08	0.42

Table 5. Nutrient digestibility in calves 15 to 16 weeks of age fed high starch texturized (**TX**) or low starch pelleted (**PL**) starters containing low (**MPL**) or high MPH) amounts of metabolizable protein. No main effect of metabolizable protein was reported. P = probability of a main effect of starch level and NS = not significant. Adapted from Hill et al., 2016a.

Digestibility, %	TX-MPL	TX-MPH	PL-MPL	PL-MPH	SEM	P
DM	84.3	84.7	79.7	78.8	0.51	0.001
OM	84.9	85.0	80.2	78.9	0.57	0.001
ADF	41.5	54.0	65.2	66.1	1.86	0.001
NDF	56.8	62.8	69.4	66.1	1.64	0.005
Starch	95.1	95.7	99.0	98.7	0.29	0.001
CP	84.9	84.6	79.5	78.6	0.54	0.001
Sugar	95.3	95.6	95.7	92.4	0.68	NS
Fat	86.3	82.7	88.3	87.8	0.78	0.08

Table 6. Estimated ME concentration (Mcal/kg of DM) in calf starters used by Chapman et al. (2016) and Hill et al. (2016b) using methods of 2001 Dairy NRC (**NRC**) or calculated using total tract digestibilities reported in each experiment. ME-allowable BW gains were calculated using equations [2-4 a-e and 2-5 to 2-10] in 2001 Dairy NRC Requirements for Dairy Cattle (NRC, 2001) or using digestibility estimates from Table 3 and Figure 2, respectively. Digestibility estimates were made at 52 to 56 days.

	Starter ME, Mcal/kg			Predicted ME, kg/day		
Item	NRC	Calculated	%	NRC	Calculated	%
Chapman et al., 2016						
CON	2.81	2.59	92	0.77	0.67	87
MOD	2.81	2.56	91	0.93	0.82	88
AGG	2.84	2.30	81	0.94	0.70	74
Hill et al., 2016b						
MOD-	2.81	2.52	90	0.83	0.71	86
AGG-	2.89	2.45	85	0.61	0.45	74
MOD+	2.83	2.60	92	0.77	0.68	88
AGG+	2.87	2.50	87	0.70	0.55	79

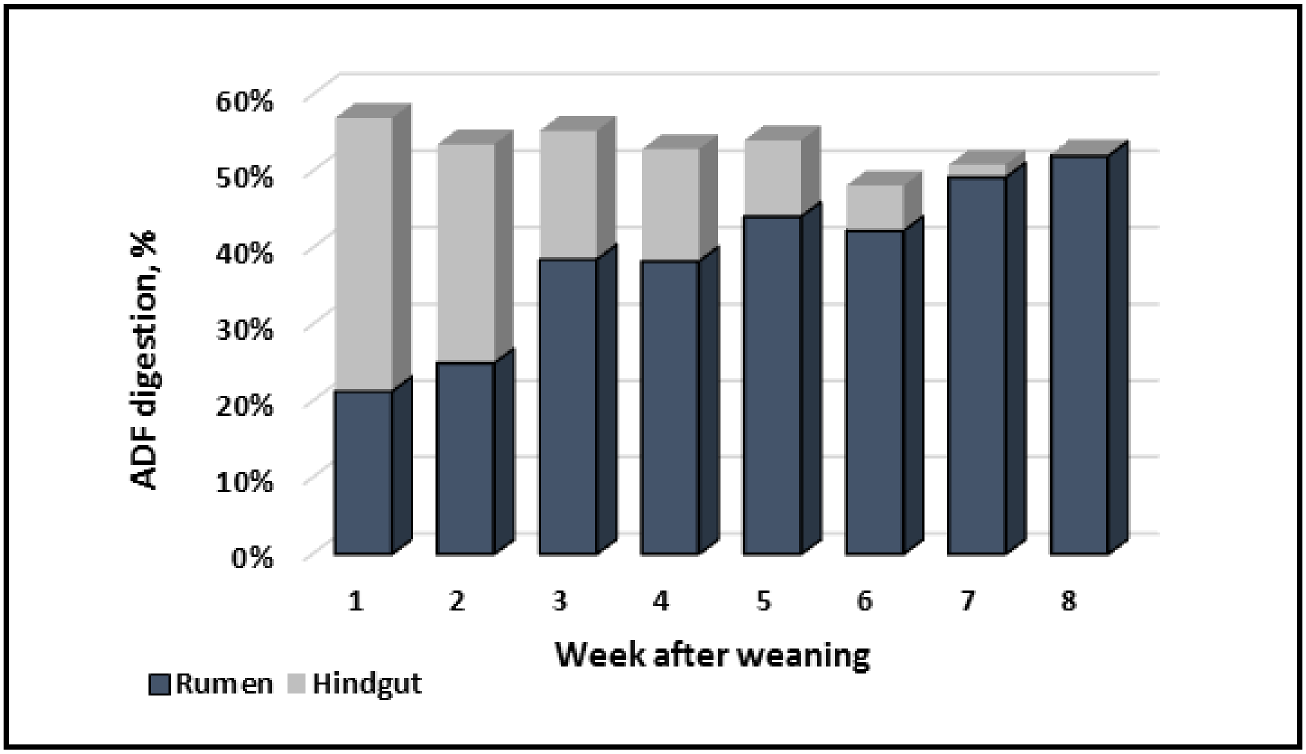

Figure 1. Digestion of acid detergent fiber (**ADF**) in calves fed milk or milk replacer to weaning at 5 weeks of age. Digestion was measured in the stomach and intestines using duodenally cannulated calves. Adapted from Leibholz, 1975.

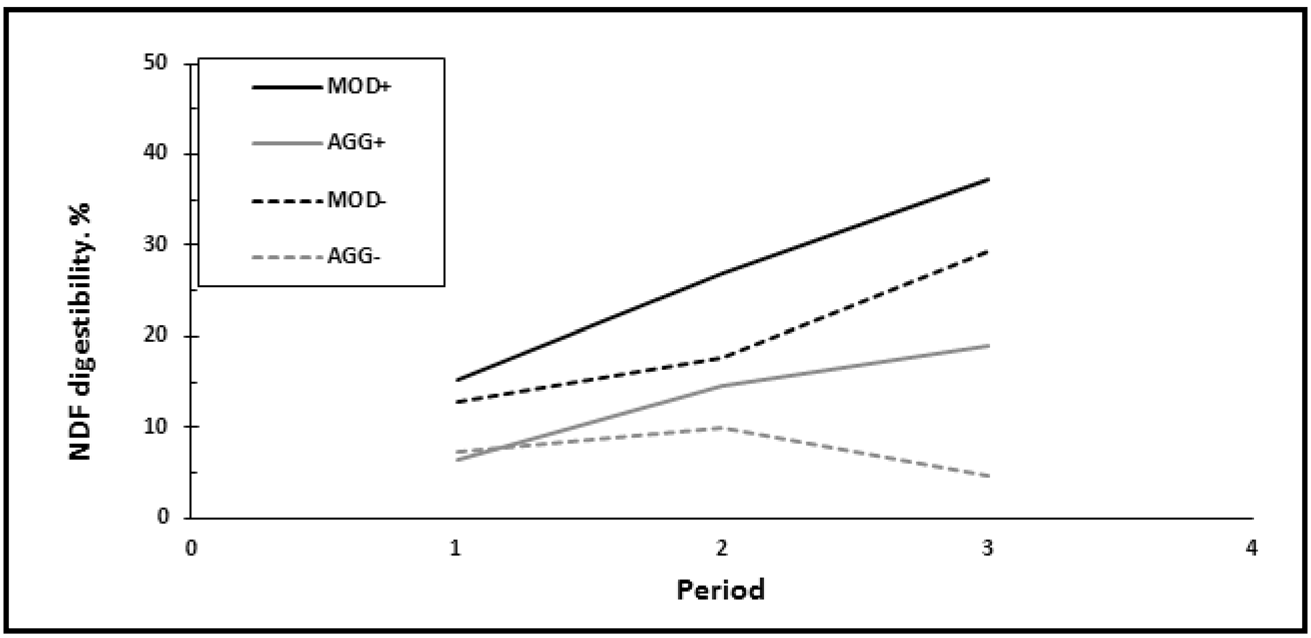

Figure 2. Change in total tract NDF digestibility in calves fed 0.66 kg of DM of a 27% CP, 17% fat MR powder daily fed for 49 days (MOD) without (-) or with (+) added NeoTec4 feed additive; or 0.66 kg of DM of a 27% CP, 17% fat MR powder fed for 4 days, then 0.96 kg of DM for 4 days, then 1.31 kg of DM fed for 34 days, then 0.66 kg of DM for 7 days (AGG). Effect of feeding level, NeoTec4 inclusion, and age were significant ($P < 0.05$). Digestibility periods were 1 = 19 to 23 days; 2 = 40 to 44 days; and 3 = 52 to 56 days of the study. Calves were 2 to 3 days of age at initiation of the study. Adapted from Hill et al. (2016b).