ABSTRACT

Early weaning Holstein dairy calf programs used low milk-replacer feeding rates and fat levels to limit feed costs, foster calf-starter intake, and facilitate rumen development. Milk replacers in those programs contained about 22% CP on an as-fed basis, from 8 to 15% fat, and were fed to wean calves at about 1 mo of age. Later milk replacers migrated to contain about 20% CP and fat, the proverbial 20/20 “industry standard.” As milk-replacer fat and milk-replacer feeding levels increased, this inversely affected calf-starter intake. The 2001 Dairy NRC Young Calf Model emerged at about the same time as a series of research trials at Cornell University and the University of Illinois began an accelerated feeding of milk replacers. These studies illustrated that increasing amount fed of milk replacers with higher protein concentration increased body protein deposition and growth rate without excessive fattening until milk-replacer fat percentage increased to 20% or more. Increasing average daily feeding rates beyond about 0.6 to 0.7 kg/d of DMI before weaning of higher protein (>25 to 26%) milk replacers with 15% or more fat led to reduction of calf-starter intake so that daily gain during and after full weaning decreased considerably. Male and female calves in these studies seemed unable to adjust their starter intake quickly enough on high milk-replacer feeding rates to avoid major performance decreases during and after weaning. Although potential benefits of accelerated milk-replacer feeding programs were originally postulated as reducing age at first calving, recent analyses of about 10 studies indicated primary benefits may be increased first, and possibly later, lactation milk yield.

Key words: dairy, calf, milk replacer, feeding, accelerated

INTRODUCTION

There is uncertainty as to when the practice of feeding milk replacers (MR) to dairy calves began because it depends on how “milk replacer” is defined. For instance, whole milk (WM) on the farm was often skimmed off and the fat used to make butter. The skim milk was then a by-product and often fed to calves or pigs as a MR. This is most likely why earlier fabricated MR from dried ingredients had what is now considered lower fat content. Warner (1960) conducted a trial with 120 Holstein heifer calves purchased at 3 d of age. Calves were fed 81.7 kg of liquid WM, or 11.35 kg of 2%-nonspecified-fat MR, 25% coconut-fat MR, or 25% lard MR (DM basis). Amount of WM fed was based on having the same digestible energy as the latter 2 MR with greater concentrations of fat when they were reconstituted at 0.227 kg per 4.09 kg of water and fed twice daily for 22 d. After 22 d on this daily feeding regimen, only one-half this amount was fed for the next 6 d followed by complete weaning. An open formula commercial calf
Early Weaning Programs

The 1950s, 1960s, and into the 1970s were a golden age of studies on rumen development in dairy calves (Warner, 1991). The primary approach then was to minimize the cost and amount of MR fed and to wean early by encouraging CS intake. An example of this program (Porter et al., 2007, trial conducted in 1972–1973) is where calves were fed a total of 9.7 kg of dry MR reconstituted with water, were abruptly weaned when they consumed an average of 0.7 kg/d of CS for 4 to 5 d, and averaged 28 d on trial when fully weaned. Several MR were used and ranged on an air-dry basis from 22 to 24% CP with 8 to 20% fat (J. C. Porter, 2009, Cooperative Extension Emeritus, Boscawen, NH, personal communication). The ADG before weaning was only 0.16 kg with 0.34 kg daily CS intake, but the study was also done to highlight effects of 4 CS studied. For 4 wk following weaning, ADG was 0.57 kg with daily CS intake averaging 1.6 kg. Calf starter was made available free choice.

A review of 22 published studies from 1967 to 1977 (Kertz et al., 1979) found an average weaning age of 32 d (range of 19 to 52) and an average daily air-dry milk–MR fed of 0.39 kg (range of 0.25 to 0.74), an average daily CS intake of 0.30 kg (range of 0.12 to 0.59). Only 5 studies fed forage, and daily air-dry intake in these studies averaged 0.09 kg and ADG averaged 0.30 kg (range of 0.09 to 0.50). These studies were compared with 5 studies with 18 treatments summarized over a 3-yr period (Kertz et al., 1979) at the Purina calf research facility in Gray Summit, Missouri. All calves were weaned at an average age of 31 d comprising a 28-d MR feeding period after 3 d of colostrum and transition milk feeding. All calves were fed 0.227 kg/d of dry MR reconstituted into 1.89 L of water and fed twice daily for 3 wk followed by only one feeding during the fourth week before full weaning. Average daily CS intake over 4 wk was 0.46 kg (range of 0.31 to 0.66) and ADG averaged 0.32 kg (range of 0.21 to 0.46). All MR fed contained 22% CP on an as-is dry-powder basis, and fat content averaged 9.8% on an as-is dry-powder basis with a range of 8 to 15%. The major variable in all of these studies (Kertz et al., 1979) was source of protein in MR. Soy flours, some soy protein concentrates, and some fish protein sources resulted in reduced ADG with accompanying lower CS intake when these protein sources provided one-half of total MR CP. Reduced CS intake was similar to the effect of poorer-quality protein sources seen in monogastrics, which often resulted in less intake and ADG. Calf trial treatments that resulted in ADG of less than 0.32 kg (average of 0.26), 0.32 to 0.36 kg (average of 0.33), and greater than 0.36 kg (average of 0.41) were associated with average CS intakes of 0.40, 0.48, and 0.58 kg/d. Consequently, regressing total BW gain on average daily CS intake with initial BW as the covariate resulted in CS intake representing 65% of the variation in ADG. Calf starter intake represented an increasing proportion of the total daily nutrition of the calf averaging 11, 28, 46, and 76% during wk 1, 2, 3, and 4. With this early weaning program employing limited MR feeding, CS becomes the major source of nutrition and has directly related to BW gain.

Fat and Protein Levels in MR

After the 1970s, based on my experiences and opinion, MR protein levels progressed down from 22 to 20% and fat levels progressed up from 10 or 12 to 20%. This was related more

<table>
<thead>
<tr>
<th>Diet</th>
<th>No. of calves</th>
<th>ADG, kg</th>
<th>CS intake, kg/7 wk</th>
<th>Dry intake of liquid, kg/4 wk</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM</td>
<td>30</td>
<td>0.49</td>
<td>35.4*</td>
<td>10.6</td>
</tr>
<tr>
<td>2%-fat MR</td>
<td>30</td>
<td>0.48</td>
<td>39.7*</td>
<td>11.4</td>
</tr>
<tr>
<td>25% coconut-fat MR</td>
<td>30</td>
<td>0.47</td>
<td>35.7*</td>
<td>11.4</td>
</tr>
<tr>
<td>25% lard MR</td>
<td>30</td>
<td>0.43</td>
<td>34.2*</td>
<td>11.4</td>
</tr>
</tbody>
</table>

a,b P < 0.05, means in columns differ if superscripts differ among means.

1Whole milk fed was calculated to have the same digestible energy as the 25%-fat MR.

2Fat source was not specified.

Table 1. Daily gain and calf starter (CS) intake for calves fed several whole milk (WM) and milk replacer (MR) diets up to 7 wk of age (Warner, 1960)
to marketing and controlling feeding costs with the nutritional benefit being that higher fat levels increased energy intake of calves from MR. As fat levels increased, costs increased, so protein level was decreased to help offset much of that increased cost. Thus the industry standard 20/20 MR evolved. This scenario was independently confirmed by M. A. Fowler based on his experiences and opinion (2010, retired from Land O’Lakes, Ames, IA, personal communication), who also noted a trial conducted by Bringe and Barr (1979). This trial was done during the months of December through April in calf hutchs in Wisconsin. Calves were fed twice daily 0.226 kg of MR. All MR contained 22% CP with 10, 15, or 20% fat levels. Weaning occurred at 24 d, but calves continued on the trial through 36 d. This very early weaning resulted in ADG of about 0.38 kg, whereas 36-d ADG and CS intakes were 0.69, 1.09, and 1.02 and 0.77, 1.03, and 1.03 kg/d, respectively, for the 3 MR fat-level treatments. Thus there was no advantage for 20 versus 15% fat in MR, but 10% fat numerically reduced ADG and CS intake compared with 15 and 20% fat in MR under those conditions (both A. F. Kertz and M. A. Fowler shared these conclusions).

Another study (Kuehn et al., 1994) illustrated that an unintended consequence resulted when fat content was increased in MR. A trial was conducted from March through October. A total of 120 calves at 3 Minnesota locations (2 used outdoor hutchs) were started on trial at 14 d of age. For their first 4 d, they had been fed colostrum and transitional milk, and that was followed by being fed a 21.4% CP and 21.6% fat DM-basis MR until d 14. No CS was fed during this period. In a 2 × 2 factorial arrangement, calves were then fed 20% CP MR on a DM basis with either 15.6 or 21.6% fat and texturized CS with either 3.7 or 7.3% total fat with the difference in fat coming from inclusion of ground roasted soybeans. Beginning at d 14, calves were fed MR at 8% of birth weight until d 36, when this feeding rate was reduced by one-half until full weaning at d 42. Starter and water were available free choice from d 14 to 56 with no forage fed. Before weaning, calves consumed more CS (P < 0.01) and gained more BW (P = 0.04) when fed the lower 15.6%-fat MR. There was some carryover effect postweaning as CS intake continued greater (P = 0.04) for the 15.6%-fat MR although ADG difference decreased and no longer was significantly different. The reason for this difference in ADG before weaning was evident when ME intakes (Table 2) were calculated. Greater CS intake on the 15.6%-fat MR treatment more than compensated for the reduced ME MR intake on this treatment. Overall effect was 7% more ME intake on the low-fat MR treatment. This similar level (7%) of higher ME intake continued from CS alone even after calves had been weaned for 14 d. Thus, the greater ME intake from the 21.6%-fat MR was more than compensated with reduced CS ME intake resulting in less total energy intake compared with a low-fat MR treatment. This effect is virtually ignored when high-fat MR are recommended. Granted, this study did not cover cold-weather months of November, December, and January. Also, not generally acknowledged is added value of heat of rumen fermentation (Russell, 2002) from CS in meeting energy requirements during cold weather. Addition of roasted soybeans reduced (P < 0.05) CS intake and ADG after weaning. This is consistent with other studies in which fat level is increased in CS.

During cold weather there are several options to increase energy intake from MR (Kertz, 2008). More MR can be fed, a greater fat level can be used in the MR, or a fat supplement can be added to the liquid feeding program. Simply feeding more MR may seem like the best approach but that means protein will be overfed because colder weather has little effect on increasing protein requirement (NRC, 2001). A greater-fat-level MR could be used, but that means inventorying another MR and may lead to overfeeding energy, depending on the weather, age, and CS intake of calf. The last option of using a fat supplement may provide the greatest flexibility but still requires some management decisions and practices to implement (Kertz, 2008). If CS and water are made available, calves may also eat more CS. Early intake of CS was encouraged by offering CS free choice in a dry Braden bottle, but calves varied in how quickly they showed interest in the bottles (McGahee et al., 1992). However, calves may spill considerable CS when using these bottles. Although heat of rumen fermentation from consumed CS does not get used to support ADG directly,

### Table 2. Calculated daily megacalories of ME intakes from milk replacer (MR) and calf starter (CS) for treatments differing in MR fat level (Kuehn et al., 1994)

<table>
<thead>
<tr>
<th>Item</th>
<th>15.6</th>
<th>21.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>d 14–42, Mcal of ME intake/d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MR</td>
<td>1.56</td>
<td>1.71</td>
</tr>
<tr>
<td>CS</td>
<td>1.86</td>
<td>1.50</td>
</tr>
<tr>
<td>Total</td>
<td>3.43</td>
<td>3.21</td>
</tr>
<tr>
<td>ADG, kg</td>
<td>0.50a</td>
<td>0.43a</td>
</tr>
<tr>
<td>d 42–56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>5.26</td>
<td>4.94</td>
</tr>
<tr>
<td>ADG, kg</td>
<td>0.95</td>
<td>0.93</td>
</tr>
</tbody>
</table>

a,b Means with different superscripts within a row differ (P < 0.05).
it spares the calf using some dietary energy intake for maintenance during colder weather. But calves less than 3 wk of age (Figure 1) have limited CS intake and are least likely to significantly increase CS intake.

If calves are fed MR for a longer duration, at a greater level, and with a higher fat content, there is a substitution effect. The greater these factors are, the more negatively they will affect CS intake. Greater fat level in the MR reduced CS intake as just noted in the study by Kuehn et al. (1994). When MR contained 12% fat, and calves were weaned at either 4 or 6 wk (Kertz, 1987), CS consumed was 0.9 kg less for each kilogram more dry MR consumed from 4 to 6 wk weaning age. But when WM (~28% fat on DM basis) was fed and calves were weaned at either 4 or 8 wk (Quigley et al., 1985), amount of pelleted CS consumed was 1.8 kg/d more for the period of 5 through 8 wk. Thus, there is a considerable range in amount of energy from milk–MR fed and its effect on CS intake. Studies in which step-up or step-down MR or milk feeding programs were used have revealed variable results and are often confounded by differences in MR dilution and feeding levels, weaning program used, physical nature of calf starter fed, and types and amounts of hay fed (Hill et al., 2007c; Khan et al., 2007).

A confounding factor in consumption of CS is the availability of clean water. Calves consume 4 times more water than DMI from CS (Kertz et al., 1979). This ratio before weaning is less (2 to 1) when not also considering water mixed with MR, and then this ratio quickly decreases to 4 to 1 after weaning (Quigley et al., 2006). This ratio of 4 to 1 water/DMI appears to continue after the calf period; recent studies showed a similar relationship in growing heifers (Lascano and Heinrichs, 2011) and lactating dairy cows (Kramer et al., 2009).

**Use of NRC Young Calf Model for Evaluation of MR Feeding**

There are a variety of liquid feeding programs used by dairy farms in the United States (NAHMS, 2007). Larger herds use more nonmedicated MR, more pasteurized waste milk, and less unpasteurized saleable milk than do smaller herds (Table 3). But it also is evident that many dairies use a combination of liquid feeds for their calves because the last column sums to 136% (NAHMS, 2007). Evaluation of liquid calf feeding programs depends on complete and accurate input information.

The 2001 NRC provided an iterative program in the Young Calf Model to evaluate responses to various calf-feeding programs. This program was the best information available in 2000 when that program was developed. It was used to illustrate how MR feeding programs would provide for energy-allowable daily gain (EDG) and protein-allowable daily gain (PDG) using a single widely recognized program. If fed, such programs may or may not provide these results, nor have studies been done to verify these results. Because of many variables present among calf trials (Kertz and Chester-Jones, 2004), and because this program only had BW and ambient temperature as variables, results would certainly vary in trial or in practice. Consequently, these results should be viewed in context as being comparative, not absolute results. For most of the graphs used in this paper, a zone of thermal neutrality was set and a temperature of 20°C was used, and both EDG and PDG were plotted for the respective BW. Intervals of 4.54 kg of BW illustrate typical BW that would be experienced by Holstein calves in their first several months of life.

Using a 20/20 MR fed at 0.227 kg mixed into 1.89 L of water and fed twice daily (Figure 2), the Young Calf Model indicated only enough CP and energy for just over 0.25 kg of ADG when a calf weighed 43.1 kg. As a calf increased in BW, and thus maintenance energy requirements increased,
EDG rapidly decreased while PDG decreased much less rapidly. Thus, more MR is needed for an increased ADG with increasing BW. If the 20/20 MR were fed at 0.68 kg divided into twice daily feedings, amount of water per MR fed as a liquid must be increased to 2.84 L twice daily to maintain the same ~12.5% solids. If not done, osmolality would be unduly increased, which could lead to some degree of digestive upset and predispose the calf to a Clostridia problem. Veterinary studies found that doubling osmolality from 360 to 717 mOsmol/L decreased abomasal emptying rate (Nouri and Constable, 2006), and conditions that provide a highly fermentable substrate and bacterial flora can facilitate production of gas and acid from bacteria such as Clostridia, Sarcina, Lactobacillus spp., and other microbes that may provide appropriate enzymes (Panciera et al., 2007). Based on laboratory analyses (Covance Laboratories, Madison, WI), osmolality in mOsmol/L increased from 261 to 10.7% solids to 330 at 13% solids with a 20/20 MR, was 428 at 13% solids for a 28/15 MR, and tested from 493 at 15.2% solids to 644 at 18.3% solids with a 28/20 MR. Milk of cows averages about 270 to 644 at 18.3% solids with a 28/20 MR, was tested from 493 at 15.2% solids to 300. However, abomasal bloating, similar to milk-fat depression in cows (Lock et al., 2006), is multifactorial and can predispose calves to Clostridia and digestive upsets. Other factors can be feeding a large volume of MR once daily, feeding cold MR, feeding poorly mixed MR, not offering water to calves, having erratic feeding schedules, and having sudden changes in MR source, but greater osmolality would rank at the top (G. W. Smith, 2011, North Carolina State University College of Veterinary Medicine—Ruminant Medicine, Raleigh, personal communication). Currently, many have increased the typical 0.45 kg/d feeding rate to 0.57 kg/d of MR in 3.78 L divided into twice-daily feedings. That program provides approximately 15% solids, the practical upper-limit MR feeding level noted before.

Increasing MR feeding rate to 0.68 versus 0.45 kg/d resulted (Figure 3) in doubling ADG to greater than 0.454 kg/d initially, EDG being greater than PDG initially, and then much less of a decrease of EDG, which is now more closely matched to PDG. This assumed pattern is likely high for MR feeding levels above 0.454 kg/d. Adding these assumed CS intakes to Figure 3 resulted in Figure 1. Daily gain due to the additive effect of MR and CS would have been above 0.454 kg/d starting at 57 kg of BW, and during week of 66 kg of BW, ADG would have been almost 0.68 kg. During once-daily MR feeding week, ADG would have decreased to about 0.454 kg/d until the following week of 75 kg of BW when CS intake would have doubled to 1.8 kg/d. This increased ADG to the target range of 0.8 to 0.9 kg/d, which is the goal for the entire postweaning period for heifers up until first calving (Kertz et al., 1998, http://www.calfandheifer. org/?page=GoldStandardsII, accessed February 5, 2012). In a metaanalysis based on 8 published studies with ADG range of 0.6 to 1.1 kg/d, Zanton and Heinrichs (2005) found that prepubertal ADG was associated quadratically with first-lactation production. Subsequent milk production, FCM production, and adjusted first-lactation milk production were maximal at about 0.8 kg of ADG prepubertal. But prepubertal ADG did not include the preweaning period; the literature review in Zanton and Heinrichs (2005) acknowledged that results from various published studies are mixed, and thus, only 8 studies were found to meet the authors’ criteria for the meta-analysis.

**Advent of Accelerated MR Feeding and Related Research Trials**

In 2001, Tikofsky et al. published a study in which Holstein bull calves were fed a constant energy level and isonitrogenous MR that differed in having 15, 21, or 32% fat. No CS was fed. Intakes were adjusted weekly resulting in a similar daily empty BW gain of 0.62 kg. Final target BW of 85 kg was selected because this is an upper limit at which most commercial
dairies feed MR before weaning. Because there is an established inverse relationship between body water and fat content (Reid et al., 1955), body composition data (Tikofsky et al., 2001) were plotted on a moisture-free basis (Figure 4). Fat content of empty BW was greater \( P < 0.006 \) for 32 versus 21% fat and for 21 versus 15% fat. Fat content of empty BW, without correction for moisture content, was 8.5 for 15%-fat MR, 9.9 for 21%-fat MR, and 11.5% for 32%-fat MR. Because ADG were the same across treatments, Figure 4 shows that percent body fat progressively increased with percent fat in MR, whereas both percent CP and ash in empty BW proportionately decreased. Based on this study, 15% fat was the optimum level in an accelerated MR program. Granted no CS was fed, but in Kuehn et al. (1994), the 15%-fat MR was also optimal when fed with CS in a more conventional MR feeding program.

Other studies reviewed below indicated that accelerated (also termed biologically normal, enhanced, or intensive, i.e., greater than typical traditional MR feeding programs) programs had beneficial results on ADG and composition of BW gain. Diaz et al. (2001) used Holstein bull calves that were fed a 30/20 MR from birth to 105 kg of BW with no CS for targeted ADG of 500, 950, and 1,400 g/d. After the 3- to 5-d adjustment period during which MR was reconstituted to 15% DM, respective treatments resulted in actual ADG of 560, 973, and 1,103 g/d from MR intake of 0.86, 1.40, and 1.38 kg/d. All calves were slaughtered for body composition data at predetermined BW of 65, 85, and 105 kg. Calves on the lowest ADG treatment had greater water content than did the higher rates of ADG treatments, reflecting that they also had less body fat. But they had more CP as a percentage of empty BW than both greater ADG treatments. Ash content was similar for lower versus the greatest ADG treatment, but the intermediate ADG treatment had the lowest \( P < 0.05 \) ash content.

Blome et al. (2003) fed male Holstein calves isocaloric MR (12.5% solids) with 20% fat and increasing treatment levels of CP at 16.1, 18.5, 22.9, and 25.8% for 42 d at which time they were slaughtered for body-composition analyses. No CS was fed. From d 3 to 14, calves had been fed a 20/20 MR during a standardization period. Treatment MR were fed at

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**Figure 2.** Predicted protein-allowable daily gain (PDG) and energy-allowable daily gain (EDG) using the NRC 2001 Young Calf Model and a milk-replacer (MR) feeding program of 0.227 kg/d of a 20%-CP and 20%-fat MR mixed into 1.89 L of water and fed twice daily. Color version available in the online PDF.

**Figure 3.** Predicted protein-allowable daily gain (PDG) and energy-allowable daily gain (EDG) using the NRC 2001 Young Calf Model and a milk-replacer (MR) feeding program of 0.34 kg/d of a 20%-CP and 20%-fat MR mixed into 2.84 L of water and fed twice daily. Color version available in the online PDF.
energy, percentage of fat in empty BW gain and in the final empty BW, and concentrations of IGF-I and insulin in plasma. But percentages of water and protein in empty BW decreased with increased feeding rate. Increasing MR CP decreased empty BW fat content while it increased CP and water content. Thus increased MR CP, and when fed at a higher daily rate, increased ADG and accompanying CP and water proportions. Ash was not changed at reduced feeding rate by MR CP, but the higher feeding rate did increase ash compared with the lower feeding rate with some increase of CP as well. Interestingly, authors noted, “These dietary effects on body composition and growth are not predicted by current (e.g., 2001) NRC standards.” These differences were that the 2001 NRC does not account for the differences that dietary protein:energy have on body composition gain and that partial efficiency of conversion of ME to retained energy was lower and more variable than the constant of 65% used by 2001 NRC. The latter was attributed to older studies that fed heavier and fatter calves WM or skim-milk-based MR more typical of veal production.

Brown et al. (2005) purchased female Holstein calves and fed them for slaughter at either 8 or 14 wk of age. They were weaned at 7 wk of age after having been fed a 20/20 MR at 1.1% of BW reconstituted at 11.8% solids and split into 2 equal feedings or having been fed a 28/15 MR at 2% of BW reconstituted at 14.1% solids. Dry matter content of MR is typically about 95%. Free-choice water was available along with a single CS fed at restricted intake to achieve 0.4 kg/d of ADG. Calves remaining after 8 wk were split further into CS fed at either restricted to achieve 0.4 kg/d of ADG or ad libitum with addition of 30% rolled corn beginning at 9 wk of age. At 8 wk, calves gained 0.668 versus 0.379 kg/d on 28/15 MR versus 20/20 MR with 2.3 cm more wither height. There were no differences in proportions of water, CP, fat, and ash in carcass between the 2 treatments, although carcass weight on the 28/15 MR was 29% greater than that on the 20/20 MR. After 8 wk, the remaining calves were split into either limited or free-choice CS treatments within each of the previous 2 to 8 wk treatments. At 14 wk, there were no differences in protein or ash proportions in carcasses, but both ad libitum CS dietary treatments had greater fat content than did limited CS diets. Calves fed ad libitum CS exceeded the 1-kg ADG, an upper limit target sometimes used for identifying fattening calves. Another trial was initiated with similar treatments and MR fed during first 6 wk until weaning at that age but without restricted CS feeding (Davis Rincker et al., 2011). Similarly, increased ADG and wither height resulted at weaning for 28/15 versus 20/20 MR feeding programs.

**Accelerated Feeding Programs**

Questions as to how accelerated MR feeding programs perform in relation to interaction between MR feeding level and CS intake, ADG, and weaning transition were addressed in several studies (Stamey, 2008; Stamey et al., 2012). In the first study (Stamey et al., 2012), Holstein female and male calves were fed either a conventional 20/20 MR with 12.5% solids at 10% of birth weight daily in 2 feedings from wk 1 to 5 and at 5% once daily during wk 6 or a 28/15 MR with 15% solids at 1.5% of BW as DM during wk 1, 2% of BW as DM during wk 2 to 5 divided into 2 daily feedings, and at 5% of birth weight during wk 6 in one daily feeding. All calves were weaned at the end of 6 wk. The 28/15 MR feeding program contained 2 CS treatments of 18 or 22% CP as fed or 19.6 and 25.5% CP DM basis, which were combined into one data set for the graphing comparison (Figure 5) because there were no differences (P > 0.10) between the 2 starter treatments. A corollary study was done with bull calves, which also found no difference between the same 18 and 22% CP starters (Stamey, 2008). Feeding less 20/20 MR (P < 0.01) resulted in greater CS intake (P < 0.02) but less ADG and height increase (P
< 0.02) than 28/15 treatments during preweaning. Total MR intakes were 19.3 for 20/20 and 34.7 kg for 28/15 with CS intakes before weaning of 14.0 and 7.3 kg, respectively. With greater DMI from MR, DMI of CS was reduced on 28/15 MR. But total nutrient intake was greater on 28/15 resulting in greater (Figure 6) ADG except for wk 7, which was just after full weaning. Figure 5 shows that loss in 28/15 MR DMI with full weaning was not equalized by CS DMI versus 20/20 MR treatment during wk 7, but it was in wk 8 to 10 when ADG was similar between MR treatments.

The second study (Stamey, 2008) was used to compare a 20/20 as-fed DM MR feeding program (conventional—CON) with an 18% CP as-fed DM CS to a 26/18 as-fed DM higher-level MR feeding program (moderate—MOD) with a 20% CP as-fed DM CS to a 28/20 as-fed DM highest-level MR feeding program (aggressive—AGR) with a 22% CP as-fed DM CS. Each MR was fed at different levels, but all calves were weaned at the end of 6 wk of age and kept in individual hutches until the end of 9 wk of age. After that they were group fed in super hutches until 12 wk of age. As MR feeding level increased to 15.8, 31.4, and 38.2 kg by treatments for the entire 42-d preweaning period, respectively, CS intake preweaning decreased inversely to MR intake at 42.1, 19.9, and 11.3 kg (Figure 7). This CS intake pattern continued to a lesser extent postweaning during wk 7 to 9. Preweaning ADG followed the pattern of daily MR intake at 0.43, 0.55, and 0.62 kg/d, respectively. Postweaning ADG was 0.99, 1.07, and 0.82 kg/d, respectively, with AGR 28/20 MR treatment being less than the MOD 26/18 MR treatment. The MOD 26/18 MR treatment carried over its intermediate ADG preweaning into intermediate CS intake but with highest ADG of 1.07 kg/d postweaning. This reflects that the AGR 28/20 MR treatment calves gained more preweaning because of greatest MR consumed, but the lowest CS intake preweaning carried over into the lowest CS intake postweaning for this treatment. The MOD 26/18 MR treatment had the best overall scenario among these treatments. In particular, Figure 8 shows that although AGR 28/20 MR had the highest ADG for the first 4 wk, that ADG decreased the most during wk 6 of one-half MR feeding and did not catch up until wk 9. Less CS intake on this treatment would have been related to higher MR fat level and greatest level of feeding of MR among treatments.

In a study with a 26/17 MR fed at or above 0.65 kg/d, Hill et al. (2007b) found that CS was decreased while ADG was similar or decreased in all trials in this study. When both 26/17 and 28/20 MR were fed at a high daily rate of 0.89 kg/d, ADG were similar by weaning with no differences in CS intake. A similar pattern was observed in the relationship among MR fed, CS intake, and ADG in most trials reported by Hill et al. (2007c, 2010), especially when MR fat level is

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**Figure 5.** Milk replacer (MR) and calf starter (CS) DMI of calves fed either a 20% CP/20% fat or 28% CP/15% fat MR (Stamey et al., 2012). Color version available in the online PDF.

**Figure 6.** Weekly ADG for 20% CP/20% fat and 28% CP/15% fat milk replacers for pre- and postweaning periods (Stamey et al., 2012). Color version available in the online PDF.
Dairy calf milk-replacer feeding programs

also taken into account. Body condition data were not available in these studies. Also, although there is great field popularity in feeding CS with greater than 18% DM CP, no calf performance benefit was found (Hill et al., 2007a). This was consistent with the authors’ finding that predictions from the 2001 Dairy NRC Young Calf Model found energy, not protein, to be most commonly limiting in CS for calf ADG. Thus CS intake is the key variable.

The 2001 Dairy NRC Young Calf Model, which provided a basis for energy and protein requirements of calves, was derived from data published before 2000. Based largely on studies reviewed in this paper (Diaz et al., 2001; Tikofsky et al., 2001; Blome et al., 2003; Bartlett et al., 2006; J. K. Drackley, 2010, University of Illinois, Champaign-Urbana, personal communication) energy and protein requirements were updated (Van Amburgh and Drackley, 2005; Table 4). For calves to grow faster, they either need to be fed more milk or MR or consume more CS if they are older calves and requirements need to be adjusted if calves are outside the zone of thermal neutrality. The 2001 NRC uses 15 to 25°C for this zone for calves less than 21 d of age. Cold weather has the most effect on increased maintenance energy requirements, although heat stress can also increase requirements, which have not yet been well quantified.

Some key comments about Table 4 requirements are that amount of milk solids required to meet maintenance requirements is sizeable, about 1.75 Mcal/d for a 45.4-kg calf (Drackley, 2010). Whole milk has about 5.37 Mcal of ME/kg of solids. Hence a 45.4-kg calf requires about 0.32 kg of milk solids or 2.54 kg of WM (~2.46 L) just for maintenance. Milk replacers are lower in fat than is WM, so 0.38 kg of MR (4.6 Mcal of ME/kg) would be required for the 45.4-kg calf to meet its maintenance requirements under thermoneutral conditions. Comparisons of WM to MR depend on the objectives of a liquid feeding program, economics, and preferences.

Table 4. Nutrient requirements and estimated G:F for a 50-kg calf under thermal neutral conditions, using the Cornell-Illinois modification of NRC (2001) equations (Van Amburgh and Drackley, 2005)

<table>
<thead>
<tr>
<th>ADG, kg/d</th>
<th>DMI, % of BW</th>
<th>ME, Mcal/d</th>
<th>CP, g/d</th>
<th>CP, % of diet DM</th>
<th>Estimated G:F</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>1.05</td>
<td>2.34</td>
<td>94</td>
<td>18.0</td>
<td>0.38</td>
</tr>
<tr>
<td>0.40</td>
<td>1.30</td>
<td>2.89</td>
<td>150</td>
<td>22.4</td>
<td>0.63</td>
</tr>
<tr>
<td>0.60</td>
<td>1.57</td>
<td>3.49</td>
<td>207</td>
<td>26.6</td>
<td>0.77</td>
</tr>
<tr>
<td>0.80</td>
<td>1.84</td>
<td>4.40</td>
<td>253</td>
<td>27.4</td>
<td>0.86</td>
</tr>
<tr>
<td>1.00</td>
<td>2.30</td>
<td>4.80</td>
<td>318</td>
<td>28.6</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Figure 7. Dry matter intakes (DMI) of protein/fat percent milk replacer (MR) treatments and of accompanying calf starter (CS) treatments (Stamey, 2008). Color version available in the online PDF.

Figure 8. Average daily gain (ADG) with milk replacer treatments of protein/fat percent during 9 wk with full weaning at the end of 6 wk (Stamey, 2008). Color version available in the online PDF.
For calves to grow faster, they need to be fed more milk or MR. As calves get bigger and older they can and should be eating more CS, but the substitution factor will be somewhat limiting because of the inverse relationship between amount of milk or MR fed or consumed and resultant CS intake. But this depends on how well the CS is integrated into the calf program. Important factors are amount of milk or MR fed, its fat or energy level, when CS is initially fed and how much at the early stages of intake (Kertz et al., 1979), physical form and fines (small particle sizes), level of CS (Porter et al., 2007), and how well water is being made available (Kertz et al., 1984). The ratio of water intake to CS DMI is typically 4:1, as has also been observed by Quigley et al. (2006), especially after weaning. An offsetting factor leading to greater CS intake is that as calves get larger, their need and impetus to eat more also increases with increasing BW.

Dietary protein and energy intakes must be matched dependent on expected growth. For example, if a 20% CP/20% fat MR is fed at twice the typical 0.454 kg/d, there will not be enough protein for lean tissue growth, and the surplus energy will be converted to fat as long as this condition exists (NRC 2001 Young Calf Model). This can be avoided if CP level is also increased with increased MR feeding level as noted by work of Bartlett et al. (2006) and Blome et al. (2003). Also in cold weather (see previous comments), some prefer to feed more MR for increased energy needs, but that wastes protein because its availability (Kertz et al., 1984) is especially critical during the first 3 to 4 wk of life when CS intake is not yet very great (Figure 1), and so calves cannot benefit much by the heat of rumen fermentation as cows do in colder weather. Long-Term Effects on Milk Production

Heinrichs and Heinrichs (2011) summarized 10 yr of data from birth to 4 mo from 795 Holsteins from 21 Pennsylvania herds. They found that difficult births and days ill of calves resulted in later age at their first calving and lower milk yield in that lactation. Growth of calves was either affected negatively or positively by DMI from milk, MR, grain, and forage. First-lactation milk yield was affected by weaning DMI, days treated for respiratory illness, and BW at calving. Lifetime production was similarly affected but to a lesser degree than first lactation. Thus a variety of negative or positive effects that occurred during the first 4 mo affected how these calves did in first and later lactations.

Although potential benefits of accelerated MR feeding were originally postulated as being due to reduced age at first calving, recent analyses by Soberon et al. (2012) indicated benefits may accrue to subsequent milk yield. Greater than 90% of calves were fed a 28/15 MR at approximately 2% of BW (0.68 kg/d from d 2 to 7) and then 0.91 kg/d until weaned by at about 42 to 49 d of age (M. Van Amburgh, 2010, Cornell University, Ithaca, NY, personal communication). Calf ADG varied from 0.10 to 1.50 kg in 1,244 heifer calves, because of management, weather, genetics, and possibly other factors (as a reference point and recommendation, 0.68 kg of ADG would double calf birth weight by the end of 2 mo of age). Feeding treatments were not imposed to create different ADG. A Test Day Model was developed (Soberon et al., 2012) using inputs of preweaning ADG, birth weight, weaning weight, calving age, birth year, birth month, and calculated energy intake over estimated maintenance requirements. For every additional 1 kg of ADG within the range of 0.10 to 1.59, heifers produced 850 kg more milk during their first lactation (P < 0.01) and produced a total of 2,280 kg over their first 3 lactations. (In a commercial NY herd fed the same MR over a 5-yr period and summarized in this paper, 623 first-lactation heifers averaged 30% greater milk response than this Cornell herd.) Preweaning ADG accounted for 22% of variation in first-lactation milk yield. Age at first calving did not affect milk production within a range of 20 to 30 mo. Colder weather for calves negatively affected subsequent milk production because less energy was available over increased maintenance needs for young calves, resulting in their reduced growth rate. For every megacalorie of ME intake above maintenance, 235 kg more milk were produced in the first lactation. Probable mechanisms for this increased milk yield are not understood but are speculated to be related to very early mammary gland development. Drackley (2010) found 10 studies that measured subsequent first-lactation milk production as related to preweaning performance. All but one of those studies (Morrison et al., 2009) had positive effects on subsequent milk production, although many are unpublished and one (Bar-Peled et al., 1998, as reviewed by Kertz, 2003) has major confounding factors that limit its value. The study by Raeth-Knight et al. (2009) was limited in finding significant lactation differences because number of animals (18 per treatment) was too limited with the variability in lactation yield. Hence more studies, analysis of data sets, and number of animals are needed to more establish this apparent relationship.

**IMPLICATIONS**

Early weaning programs emphasized limited MR feeding to limit feed costs, to increase CS intake, and to stimulate rumen development. When accelerated MR feeding programs were initiated, they emphasized feeding more MR and with a higher CP level to increase ADG more closely to the ability of a calf to grow without excessive fattening. The optimal MR fat level was 15%. Benefit from accelerated MR feeding programs was postulated to decrease age at first
calving by one or more months. But most recent data indicate the primary benefit may be additional milk yield in first and subsequent lactations related to ADG before weaning. When an additional kilogram of ADG before weaning can result in 850 kg more milk in the first lactation, this benefit would have greater economic return than a reduced age at first calving.

**LITERATURE CITED**


Kertz and Loften


