Effects of gradual and later weaning ages when feeding high milk replacer rates on growth, textured starter digestibility, and behavior in Holstein calves from 0 to 4 months of age

T. S. Dennis,* F. X. Suarez-Mena,* T. M. Hill,*¹ J. D. Quigley,* R. L. Schlotterbeck,* R. N. Klopp,†
G. J. Lascano,‡ and L. Hulbert‡

*Nurture Research Center, Provimi, Brookville, OH 45309

†Department of Animal and Veterinary Sciences, Clemson University, Clemson, SC 29634

‡Department of Animal Sciences and Industry, Kansas State University, Manhattan 66506

ABSTRACT

The objectives of this study were to evaluate calf performance, diet digestibility, and behaviors when feeding 4 milk replacer (MR) programs with different MR rates, weaning ages, and MR reduction steps. Male Holstein calves ($n = 96$; 40 ± 1 kg of body weight; 1 to 2 d of age) were housed in individual pens for 56 d. Feeding programs for MR were 0.66 kg for 35 d; then 0.33 kg for 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.1 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib). Calves were fed a common MR [25% crude protein, 17% fat, dry matter (DM) basis]. A textured calf starter with whole corn and oats (20% crude protein and 39% starch, DM basis) and water were fed for ad libitum intake during the nursery trial. Daily behavior duration (rumination, eating, and activity) was continuously recorded from d 1 to 55 for 4 calves/treatment using ear tag accelerometers (CowManager SensOor; Agis, Harmelen, the Netherlands). All calves were moved into groups by MR program (4 calves/pen) at 56 d and fed the same starter blended with 5% grass hay. Fecal samples were collected from individual calves between d 52 to 56 and from pen floors on d 66 to 70 to estimate total-tract digestibility. Data were analyzed as a randomized complete block design with repeated measures when appropriate. Intake of MR averaged 25.3, 35.3, 40.9, and 46.5 kg of DM per calf for 0.6 kg, 0.8 kg, 1.1 kg, and ad lib treatments, respectively. Starter intake was greatest for 0.6 kg compared with others and average daily gain (ADG) differed among

all 4 programs with $0.6 \text{ kg} < 0.8 \text{ kg} < 1.1 \text{ kg} < \text{ad lib}$ during d 0 to 56. Intake of MR for ad lib was highly variable and was reflected in ADG. Daily rumination, eating, and activity durations did not differ among treatments from d 1 to 55 of the nursery trial. Digestibility of DM, organic matter, acid and neutral detergent fiber, and sugar at d 52 to 56 were greater for 0.6 kg versus ad lib. Digestibility of DM at d 66 to 70 differed for all treatments with $0.6 \text{ kg} > 0.8 \text{ kg} > 1.1 \text{ kg} > \text{ad lib}$ and was mostly influenced by fiber digestibility. During the grower trial (d 56 to 112), ADG was greater for 0.6 kg versus 1.1 kg and ad lib. Hip width change was greater for 0.6 kg versus other treatments. Feeding more than 0.6 kg/d of MR increased ADG preweaning, but reduced diet digestibility postweaning resulted in similar calf BW and frame size by 4 mo of age among MR feeding programs.

Key words: calf, weaning, digestibility, behavior

INTRODUCTION

In North America, interest in feeding dairy calves large amounts of milk or milk replacer (MR) is widespread. Much of this interest has been driven by data reported by Diaz et al. (2001). In their research, calves fed increasing amounts of MR responded with increased ADG and carcass growth; however, no calf starter was fed. A major concern when feeding large amounts of milk or MR is that greater preweaning ADG and weaning BW typically observed is lost by approximately 4 mo of age compared with moderate milk or MR-feeding programs (less than 0.7 kg/d of DM). For example, BW at 52 d of age (preweaning) was 3.7 kg heavier for calves allotted up to 1.0 kg/d of MR (25% CP, 19% fat on DM basis) compared with 0.75 kg/d, but BW at 73 d (weaning) and 228 d of age was similar regardless of MR feeding rate (Bach et al., 2013). Whereas BW may be influenced by gut fill (Khan et al., 2011), structural measurements would be more accurate assessments of growth pre- and postweaning. Davis Rincker et al.

Received July 2, 2018.

Accepted July 19, 2018.

¹Corresponding author: mhill@provimi-na.com

(2011) compared a conventional MR-feeding program (21.5% CP, 21.5% fat MR fed on DM basis at 1.2% of BW with 20% CP calf starter) to an intensified program (30.6% CP, 16.1% fat MR fed at 2.1% of BW with 24% CP calf starter) and reported greater BW, withers height, and hip width at 42 d of age for calves on an intensified program; however, BW and hip widths were similar between treatments at 84 and 196 d of age, respectively. Other researchers have reported similar structural growth by 4 mo of age when calves were fed more than 0.7 kg/d of DM from milk (Kiezebrink et al., 2015) or MR (Hill et al., 2013, 2016a,b).

A potential drawback to feeding large amounts of milk or MR is that calves are less motivated to consume calf starter during the preweaning period. During weaning, starter consumption rapidly increases for calves fed high amounts of milk, whereas calves receiving 0.7 kg/d of DM or less from milk gradually increase starter consumption through the preweaning period. Lack of transitional feeding behaviors can delay rumen development, resulting in reduced starter digestibility for at least 4 wk after weaning (Terré et al., 2007; Osorio et al., 2012; Hill et al., 2013, 2016b). For example, calves allotted increasing amounts of pasteurized whole milk using computerized autofeeders averaged less than 0.1 kg/d starter intake up to 6 wk of age when fed 8, 10, or 12 L/d, whereas starter intake averaged 0.3 kg/d for calves allotted 6 L/d (Rosenberger et al., 2017). Similarly, low preweaning solid feed intakes were reported among calves on noncomputerized ad libitum systems (Nocek and Braund, 1986; Hill et al., 2013) and calves hand-fed MR at more than 0.7 kg of DM/d (Cowles et al., 2006; Hill et al., 2007, 2010).

A possible remedy to slowed growth postweaning when feeding high amounts of MR may be gradually reducing MR allowance over several days to stimulate starter intake before weaning. Several researchers have tested gradual weaning protocols in calves fed large amounts of MR (Sweeney et al., 2010; Hill et al., 2012; Dennis et al., 2018) and reported some degree of success when weaning occurred over at least a 10-d period. Additionally, Hill et al. (2016b) reported increased postweaning digestion and growth after gradually weaning high MR-fed calves over a 3-wk period compared with a 1-wk period (stepped-down from 1.1 kg/d of MR). Later weaning ages when feeding a high rate of MR have been suggested to assist in successful feeding programs when measuring BW gain to 10 wk (Eckert et al., 2015) and 13 wk (Meale et al., 2015) of age. Eckert et al. (2015) reported 8.9-kg heavier calves at 10 wk of age with 8 versus 6 wk weaning ages and Meale et al. (2015) reported 5.2-kg heavier calves at 13 wk of age with 12 versus 8 wk weaning ages. However, neither of these studies reported structural growth measurements

and post-weaning measurements were assessed over a short length of time.

Few researchers have tested a large range of MR feeding rates similar to those reported by Rosenberger et al. (2017). An issue outlined in Rosenberger et al. (2017) was incomplete intake of MR at all 4 treatment allotments. As MR allotments increased, the amount of MR not consumed from the allotment increased, possibly introducing variation and other issues to the data set. Similarly, Borderas et al. (2009a) reported calves on computerized autofeeders set to provide ad libitum intake reached a plateau in MR intake approximately 2 wk into the feeding program that was about 60% of the maximum set point (24 L/d). It would be useful to understand why calves fed with computerized autofeeders plateau in milk consumption (Miller-Cushon et al., 2013) and do not drink as much milk as calves observed in some hand-fed experiments (Hill et al., 2011).

More information on calf intake, BW and structural growth, and digestion from offering several rates of MR is needed to understand the outcomes from different feeding programs. Additionally, more information is needed 8 to 10 wk postweaning from feeding different rates of MR to understand how calves perform after the weaning transition. Therefore, the objectives of our study were to address some of the void in the literature by hand-feeding calves increasing rates of MR from 0.66 kg of DM to ad libitum allowance. We hypothesized that high feeding rates of MR with later and gradual weaning would support more growth and similar postweaning diet digestibility as calves fed a moderate amount (0.66 kg/d of DM) of MR. Additionally, we recorded rumination, eating, and activity durations 24 h per day over a 55-d period pre- and early postweaning to characterize feeding behavior in response to different MR feeding programs.

MATERIALS AND METHODS

Animals, Facilities, and Treatments

All animals were cared for as described in the *Guide for the Care and Use of Agricultural Animals in Research and Teaching* (FASS, 2010) and under approval of the institutional animal care and use committee. Male Holstein calves (1 to 2 d of age) were received at the Nurture Research Center nursery in southwest Ohio from 1 commercial dairy farm after a 3.5-h transit. The phase used 2 blocks of 48 calves received 35 d apart. The nursery included individual calf pens (1.2 × 2.4 m) with a coarse rock, tile-drained base bedded with wheat straw in a barn with curtain sides, natural ventilation, and no added heat. The grower unit consisted of group pens (4 calves per pen) with 1.4 m² of inside resting

space bedded with wheat straw and 6.5 m² of outside space with a coarse rock, tile-drained yard, and concrete pad. The first block of calves arrived September 14, 2016, and concluded treatments January 4, 2017; the second block of calves arrived October 19, 2016, and concluded treatments February 8, 2017. The average temperature during the nursery phase blocks (0 to 56 d) was 11°C (range from −15 to 31°C) with an average humidity of 82% (range from 22 to 100%). The average temperature during the grower phase blocks (56 to 112 d) was 1°C (range from −19 to 28°C) with an average humidity of 88% (range from 33 to 100%).

The day after arrival at approximately 1200 h, calves were weighed (d 0; 40.4 ± 0.99 kg of initial BW) and a blood sample was taken via jugular venipuncture. Serum was separated by centrifugation at 3,000 × *g* (VWR, Batavia, IL) at 20°C for 15 min, and serum total protein concentration was estimated using an optical refractometer (ATAGO U.S.A. Inc., Bellevue, WA). All calves were initially fed 0.66 kg of DM from MR for the first p.m. and following a.m. feeding, then randomly assigned to 1 of 4 feeding programs. Treatments were up to 0.66 kg/d of MR powder and weaned at 42 d of age (referred to as 0.6 kg); step-up to 0.82 kg/d MR of powder and weaned at 49 d of age (referred to as 0.8 kg); step-up to 1.09 kg/d of MR powder and weaned at 49 d of age (referred to as 1.1 kg); and ad libitum allowance for 35 d then step-down to weaning at 49 d of age (**ad lib**). Figure 1 illustrates the feeding timeline used in the study. The 0.6 kg treatment was included because of good success with this rate and 42-d weaning program in past trials (Hill et al., 2007, 2010, 2016a,b). We employed a step-down in MR allowance over 2 wk to gradually wean calves on 1.1 kg and ad lib to potentially avoid postweaning growth slumps, as Sweeney et al. (2010) reported calves fed up to 12 L/d of whole milk and weaned at 6 wk of age performed best with a 10-d gradual step-down weaning protocol. Calves were fed a common MR (25% CP, 17% fat on a DM basis reconstituted to 14% solids; Table 1) in equal meals at 0600 and 1530 h. During the last 7 d before weaning, MR was offered only in the a.m. feeding for all treatments. Calves on ad lib were given unrestricted access to MR for 2 h at 0600 and 1530 h. The MR was formulated with added synthetic AA (Hill et al., 2008) and fatty acids (Hill et al., 2011). Rejected MR was weighed back 1 h after each feeding (or daily for ad lib). A whole-grain, textured calf starter (20% CP, 39% starch on a DM basis; Table 1) and water were fed for ad libitum intake during the nursery phase. On d 56, calves from the nursery phase were grouped by preweaning treatment and moved to pens (4 calves/pen within treatment). Calf starter used in the nursery phase was blended with 5% chopped grass hay (ap-

proximately 2.5 cm particle length) on an as-fed basis and fed for ad libitum intake with free-choice access to water. Grower feed refusals were weighed daily to determine DMI.

Calves were weighed weekly during the nursery phase and on d 84 and 112 during the grower phase. Hip widths were measured using a caliper and BCS were assessed by palpating the transverse process by an experienced technician (1 being thin to 5 being obese; modified from Wildman et al., 1982) on d 0, 14, 28, 42, 56, 84, and 112. Feces were scored daily during the nursery phase using a 1 to 5 scale (1 being normal and 5 being watery; modified from Kertz and Chester-Jones, 2004). Fecal scores >2 were considered abnormal. Calves received oral electrolytes for diarrhea when fecal scores were >2; however, electrolytes were not counted as medical treatments. Antibiotic medical treatments were recorded daily and were administered based on a binomial scoring system of lethargy, coughing, nasal discharges, or rectal temperatures >39.4°C.

Digestibility Estimates

In the nursery phase, 5 calves/treatment from the first block of calves were randomly selected for use in digestibility analysis. During d 52 to 56 (denoted as d 52), 12 total fecal grab samples were collected such that every 2 h in a 24-h period was represented and composited by calf to estimate total-tract diet digestibility as described by Hill et al. (2016a). In the grower phase, 12 total fecal grab samples were taken from the pen floor with care not to sample bedding or other floor materials and composited by pen for use to estimate total-tract diet digestibility during d 66 to 70 (denoted as d 66). Acid-insoluble ash was used as an internal marker for feed and fecal samples taken during both periods. Feed was offered for minimal refusals during the digestibility periods (averaging 2.9% of offered) and refusals were saved daily by pen, composited, and subsampled for analysis. The nursery and group pens were bedded with long wheat straw and straw consumption by calves was possible (Hill et al., 2010, 2016a,b). This was accounted for by not adding new bedding 3 d before and during fecal collection periods to minimize the chance of straw intake during the week of digestibility measurements. Theoretically, unaccounted for consumption of straw could have reduced estimates of digestibility.

Rumination Behavior and Activity

At arrival, 4 calves/treatment in the first block were randomly assigned to have a tag that encased a 3-dimensional accelerometer placed in its ear. The ear tag (CowManager SensOor; Agis, Harmelen, the

Figure 1. Milk replacer (MR) allowance schedule for each feeding program during the nursery phase. Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib). Average MR intake from d 1 to 35 is reflected in ad libitum schedule.

Netherlands) attached to radio-frequency identification female buttons using a long male pin supplied by the company to fit through the radio-frequency identification button. Application of the accelerometer to the ear and management of the calves are described in Hill et al. (2017). Data from the ear tags were collected each minute and processed using commercially available, proprietary software algorithms. The output was hourly, mutually exclusive durations for eating (MR plus starter), ruminating, activity, and inactivity. The sensors were validated (Hill et al., 2017) using live observation with instantaneous recording and were found to be accurate at measuring rumination ($R^2 = 0.91$), eating ($R^2 = 0.75$), and activity duration ($R^2 = 0.97$) in calves 4 to 6 wk old. Eating, rumination, and activity duration (min/h) from d 1 to 55 were compared among treatments.

Feed and Digestibility Analyses

Every other bag (22.7 kg) of MR and starter and every bale of hay was sampled and composited for nutrient analysis. Feeds, refusals, and feces were analyzed (AOAC International, 2000) for DM (oven method 930.15), ash (oven method 942.05), CP (Kjeldahl method 988.05), fat (alkaline treatment with Roesse-

Gottlieb method 932.06 for MR; diethyl ether extraction method 2003.05 for starters and hay), NDF with ash by the procedure of Van Soest et al. (1991) without sodium sulfite or α -amylase, ADF with ash (Robertson and Van Soest, 1981), starch (α -amylase method; Hall, 2009), sugar (colorimetric method; Dubois et al., 1956), and acid-insoluble ash (Van Keulen and Young, 1977).

Statistical Analyses

In the nursery phase, intake and BW data were grouped by week, whereas hip width and BCS change were grouped by 14-d periods. In the grower phase, intake, BW, hip width, and BCS data were grouped by 28-d periods. Data were analyzed as a randomized complete block design with repeated measures when applicable by PROC MIXED in SAS (version 8; SAS Institute., Cary, NC). Block was included as a random effect. Digestibility data were analyzed separately by phase (nursery and grower). Behavior data (min/h) in the nursery phase were analyzed by week and over the entire nursery phase. Additionally, behavior data were analyzed by hour of the 24-h day for the phase. For all data, an auto-regressive type 1 covariance matrix was employed as determined using Akaike's information criteria. Exceptions were BCS, abnormal fecal score days,

and medical days, which were summed over the nursery phase and analyzed using Kruskal-Wallis test with PROC NPAR1WAY in SAS. Additionally, ADG and intake were evaluated using PROC REG in SAS. Calf was the experimental unit in the nursery phase and pen (4 calves/pen) was the experimental unit in the grower phase. Means were separated using PDIFF option in SAS. Significance was determined at $P \leq 0.05$.

RESULTS

Feed Intake and Growth Performance

Other than calves fed ad lib, no calf rejected MR offered. As expected, MR intake for ad lib from d 1 to 35 was highly variable (Figure 2). Intake of MR averaged 25.3, 35.3, 40.9, and 46.5 kg/calf for 0.6 kg, 0.8 kg, 1.1 kg, and ad lib, respectively. Starter intake was greater for 0.6 kg versus other treatments ($P < 0.05$; Figure 3). Calf ADG differed among all 4 programs where $0.6 \text{ kg} < 0.8 \text{ kg} < 1.1 \text{ kg} < \text{ad lib}$ ($P < 0.05$). During d 1 to 35, when calves on ad lib were allowed MR for ad libitum intake, ADG increased linearly ($P < 0.001$, $R^2 = 0.42$) as MR intake increased (Figure 4). Calf BW at 56 d was greater for 1.1 kg and ad lib versus 0.6 kg and 0.8 kg ($P < 0.05$; Figure 5). Initial hip width for 1.1 kg was greater than the other treatments ($P < 0.05$; Table 2). Calf hip width at 56 d did not differ among treatments (Figure 6). Feed efficiency, BCS change, and days with abnormal fecal scores were

Table 1. Analyses of feeds used in the current study

Nutrient ¹	MR ²	Starter ³	Hay
DM, % as-fed	96.5	88.1	85.4
CP	25.0	5.0	6.0
ADF	—	7.7	40.8
NDF	—	17.2	63.5
Sugar	—	6.0	11.3
Starch	—	39.7	0.9
Fat	17.8	3.9	1.8
Ash	5.7	6.6	7.2
ME, ⁴ Mcal/kg	4.6	3.1	2.2

¹Percent of DM unless otherwise stated.

²Milk replacer manufactured from whey, whey protein concentrate, and animal fat.

³37% whole corn, 35% protein/mineral pellet, 25% whole oats, and 3% liquid molasses.

⁴Metabolizable energy calculated using NRC (2001) equations.

least for 0.6 kg and 0.8 kg and greatest for 1.1 kg and ad lib ($P < 0.05$). Average fecal score was greater for ad lib than others ($P < 0.05$); however, medical days were similar among treatments and health events were low throughout the nursery phase.

Feed intake and other performance measurements did not differ during the grower phase (d 56 to 112). During the grower phase, ADG was greater for 0.6 kg versus 1.1 kg and ad lib ($P < 0.05$; Table 3). Hip width change was also greater for 0.6 kg versus other treatments ($P < 0.05$). Feed efficiency was least for calves previously fed ad lib compared with other treatments

Figure 2. Intake of milk replacer (MR; DM) of calves (represented by individual circles) fed ad libitum (ad lib) from 1 to 35 d. Ad lib was ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only. The line shows the average for all calves.

($P < 0.05$). Final BCS was greatest for ad lib versus others ($P < 0.05$).

Over the 112 d of both the nursery and grower phases, total DMI averaged 232, 226, 231, and 246 kg per calf for 0.6 kg, 0.8 kg, 1.1 kg, and ad lib, respectively. Feed efficiency from 0 to 112 d averaged 0.39, 0.40, 0.39, and 0.38 for 0.6 kg, 0.8 kg, 1.1 kg, and ad lib, respectively. Total hip width change averaged 9.5, 8.9, 8.7, and 8.9 cm for 0.6 kg, 0.8 kg, 1.1 kg, and ad lib, respectively. Total BCS change averaged 0.5, 0.5, 0.6, and 0.7 for 0.6 kg, 0.8 kg, 1.1 kg, and ad lib, respectively. Statistical analyses were not performed on these measurements because the experimental units differed between the nursery (1 calf) and grower (pen of 4 calves) phases. Numerically, calves fed ad lib may have had the greatest DMI and BW gain among the 4 programs; however, hip width gain and feed efficiency did not appear to differ among MR programs.

Apparent Digestibility

Total-tract apparent digestibility measurements for d 52 are shown in Table 4. Digestibility of DM, OM, ADF, NDF, and sugar were greater for 0.6 kg versus ad lib, with calves fed 0.8 kg and 1.1 kg having numerically intermediate digestibility coefficients (dC) compared with calves fed 0.6 kg and ad lib ($P < 0.05$). Appar-

ent dC for d 66 are shown in Table 5. Dry matter dC differed for all treatments with 0.6 kg > 0.8 kg > 1.1 kg > ad lib ($P < 0.05$). Organic matter, ADF, NDF, and starch dC were greater for 0.6 kg and 0.8 kg versus 1.1 kg and ad lib ($P < 0.05$). Digestibility of CP was greater for 0.6 kg and 0.8 kg versus ad lib ($P < 0.05$).

Activity, Eating, and Rumination Behaviors

Time spent ruminating, eating, active, and not active did not differ among MR programs when evaluated weekly or overall (from d 1 to 55) during the nursery phase. As calves aged, rumination and active durations increased ($P < 0.01$; Figure 7). For 24-h observations, no treatment differences were observed. All calves displayed 2 distinct eating and active periods, with inactivity in between ($P < 0.01$; Figure 8). However, rumination did not appear to have a circadian rhythm.

DISCUSSION

Feed Intake and Growth Performance

Calf ADG from d 0 to 35, when MR was fed ad lib, was linearly related to MR intake; however, the relationship was moderately weak ($R^2 = 0.42$). The variable intake of MR limited BW gain of calves fed ad

Figure 3. Starter intake by week for calves fed 4 milk replacer programs. SEM = 0.09 kg/d. Intake was greater ($P < 0.05$) for 0.6 kg vs. others in wk 6 and 7. Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

lib. Consistent intake of MR fed at 0.66 kg of DM/d has been associated with improved ADG (+23% compared with fluctuating intake; Hill et al., 2009). Variation of MR intake is not typically reported in the literature and may require more research, especially with interest in feeding greater allowances of milk or MR.

Weaning 1 wk later when feeding high rates of MR (0.8 kg, 1.1 kg, and ad lib vs. 0.6 kg) did not improve growth to 16 wk of age in the current study and another study with similar measurement made to 16 wk of age (Dennis et al., 2018), in contrast to other comparisons to 10 wk (Eckert et al., 2015) and 13 wk (Meale et al., 2015) of age. Eckert et al. (2015) reported 8.9-kg heavier calves at 10 wk of age with 8 versus 6 wk weaning and Meale et al. (2015) reported 5.2-kg heavier calves at 13 wk of age with 12 vs. 8 wk weaning. Eckert et al. (2015) and Meale et al. (2015) did not measure structural growth. Reasons for disagreement in the literature are unclear. One reason could be attributed to differences in sampling frequency and duration of measurements (to 10, 13, or 16 wk of age). Another reason could be difference in dry feeds used among the experiments. Dry feed offered in the current study differed in particle size and forage inclusion before weaning, as calves in Eckert et al. (2015) and Meale et al. (2015) were offered completely pelleted starters with

lower reported ME content and free-choice access to chopped straw. Starter intake in the first few weeks of life when high rates of MR are fed is often very low, and extended feeding of high rates of MR may not allow for adequate rumen development until significant starter intake is accumulated. Thus, improved postweaning digestion has been a benefit of gradual and later weaning to stimulate earlier starter intake (Hill et al., 2016b).

Postweaning ADG and hip width change (2 to 4 mo) were greater for calves fed less than 0.7 kg/d in the current study, resulting in BW and hip widths that did not differ by 4 mo of age. Yunta et al. (2015) fed 0.55, 0.72, or 0.90 kg/d of DM from MR (4, 6, or 8 L/d) and reported ADG was greatest for calves fed 0.90 kg/d preweaning, but BW 300 d after MR treatment initiation was similar for calves fed 0.72 and 0.90 kg/d and least for calves fed 0.55 kg/d. When Korst et al. (2017) compared computer-controlled MR intake restricted to 0.78 kg/d of DM from MR (23% CP, 17% fat) to ad libitum access to MR (>1.1 kg/d of DM from MR), preweaning ADG was greater for calves fed ad libitum MR but BW were similar at 110 d of age. Whereas frame measurements were not reported by Yunta et al. (2015) or Korst et al. (2017), BW responses postweaning were similar to those reported in the current study and by other groups that fed increasing levels of milk

Figure 4. Cumulative BW gain for calves fed 4 milk replacer programs. SEM = 1.1 kg/d. Gain was greater ($P < 0.05$) for 1.1 kg and ad lib vs. 0.6 kg and 0.8 kg in wk 3, 4, and 5. Gain was greater ($P < 0.05$) for ad lib vs. 1.1 kg and 0.8 kg in wk 6. Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

or MR (Bach et al., 2013; Hill et al., 2013, 2016a,b; Kiezebrink et al., 2015).

Even with a 2-wk gradual reduction in MR fed with a later weaning age, calves fed the 2 highest allotments (1.1 kg and ad lib) experienced reduced growth rates and starter digestibility during the extended postweaning period (2 to 4 mo of age) compared with calves fed the lowest MR allotment and weaned 1 wk earlier (0.6 kg). Note that calves fed the 3 lowest allotments of MR consumed all of their MR each day. The highest hand-fed allotment (1.1 kg) was offered a maximum of 1.1 kg of DM between 2 and 5 wk of age, similar to the maximum consumption group of 12 L in Rosenberger et al. (2017). The ad lib intake increased to a maximum of 1.5 kg of DM/d, but the variation in intake was large (Figure 1) and similar to other variation in ad libitum-fed MR intake reported from in our facility (Hill et al., 2013). Factors that drive ad libitum milk and MR intake are not clear in the published literature, but health of calves is one potential factor (Borderas et al., 2009a,b). Interestingly, in the current phase, several calves consumed less than 1.1 kg of DM in the ad lib program, whereas all calves in the 1.1 kg program consumed all their MR allotment. On d 14, when calves on 1.1 kg were increased to 1.1 kg/d of DM from MR, half the calves on the ad lib program were not yet consuming 1.1 kg/d of DM.

Apparent Digestibility

Increasing MR feeding rate increased preweaning ADG, reduced preweaning starter intake, and reduced postweaning diet digestibility. These results were similar to previous research from our group (Hill et al., 2007, 2010, 2013, 2016b, 2017) and from Terré et al. (2006, 2007). Terré et al. (2006) did not measure starter digestibility; however, during the weaning transition (10 d before through 36 d after weaning) calves fed 4 L/d had significantly greater purine derivative excretion compared with calves fed up to 6 L/d, which was correlated with starter intake and suggests greater starter digestibility for calves fed less MR. Purine derivative excretion has been used as an indirect measure of microbial protein flow from the rumen in early-weaned calves and can indicate extent of rumen development (Funaba et al., 1997). Though Terré et al. (2006, 2007) fed less DM from MR than the current study (MR composition was fairly similar to the current study), other reports have shown decreases in starter intake when calves were fed greater than 6 L/d of milk (Kiezebrink et al., 2015) or 0.7 kg/d of DM from milk replacer (Yunta et al., 2015). Reductions in DM digestion postweaning as a result of feeding more MR came from reduced digestibility of fiber and sugar; this is similar to other recent measurements in the literature (Chapman et al., 2016; Hill et

Figure 5. Cumulative hip width change for calves fed 4 milk replacer programs. SEM = 0.1 cm. Gain was greater ($P < 0.05$) for 1.1 kg and ad lib vs. 0.6 kg and 0.8 kg in wk 4 and 6. Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

al., 2016a,b). In the current study, starter was high in starch from whole corn and oats. Starch from the whole grains were highly digestible (>93%). We are not aware of other data sets where total-tract digestibility was measured 1 to 3 wk postweaning to determine carryover effects of MR feeding program.

Activity, Eating, and Rumination Behaviors

Time spent ruminating, eating (starter and MR combined), active, and not active was not different among the 4 MR programs within week or over the entire nursery phase. However, all behavior measurements were highly variable among calves. Eating and ruminating behaviors in older heifers have also been reported to have large variation (Deswysen et al., 1993). Nonetheless, more calves were likely needed per treatment to detect any potential differences in behavior.

Some experts have suggested the importance of early rumination in calves. Conceptually, calves fed 0.6 kg should have initiated rumination at an earlier age than calves fed 1.1 kg or ad lib. However, rumination and eating behaviors were not different among treatments. As expected, rumination duration increased as calves aged (Figure 7). In our study, rumination averaged 52

min/d in 1-wk-old calves and 204 min/d in 3.5-wk-old calves. Swanson and Harris (1958) reported using visual observation that rumination in preweaning calves also increased with age, as calves 1 to 2 wk old ruminated 47 min/d and calves 3 to 4 wk old ruminated 185 min/d. Similarly, Gilliland et al., (1962) reported 154 to 187 min/d of rumination in 3.5-wk-old calves. Burfeind et al. (2011) reported that calves 4, 6, and 9 wk old ruminated for 22, 26, and 28 min over a 2-h period, respectively. Additionally, rumination events occurred evenly throughout the day and were not related to a specific time of the day (Figure 8). Unlike eating and activity behaviors, rumination did not appear to have a circadian rhythm. This is in contrast to more mature ruminants, as rumination typically exhibits a circadian rhythm, with the majority of daily rumination occurring in the morning (Gordon and McAllister, 1970; Murphy et al., 1983).

Eating and activity behaviors exhibited bimodal circadian rhythms, which was most likely due to MR feeding schedules. Surprisingly, time spent active did not differ by treatment, as some studies have seen changes in activity with milk allowance. De Paula Vieira et al. (2008) reported group-housed calves fed milk at 10% of BW daily (4.2 to 4.8 L/d) were more active and com-

Table 2. Performance of calves fed 4 milk replacer (MR) programs¹ from d 0 to 56

Item	0.6 kg	0.8 kg	1.1 kg	Ad lib	SEM
Maximum MR rate fed, kg/d	0.66	0.82	1.09	ad lib	—
Initial serum protein, mg/dL	6.0	6.3	6.0	5.9	0.16
Initial BW, kg	40.5	39.1	41.9	39.9	0.99
Final BW, kg	72.5 ^a	72.1 ^a	77.3 ^b	78.6 ^b	3.68
Initial hip width, cm	16.9 ^a	16.8 ^a	17.6 ^b	16.8 ^a	0.21
Final hip width, cm	21.0 ^{ab}	20.8 ^a	21.5 ^b	21.1 ^{ab}	0.43
Initial BCS ²	2.1	2.2	2.1	2.1	0.03
Final BCS	2.4	2.4	2.4	2.4	0.06
MR intake, ³ kg/d	0.45	0.63	0.73	0.83	—
Starter intake, kg/d	0.71 ^a	0.51 ^b	0.49 ^b	0.45 ^b	0.033
Total DMI, kg/d	1.16 ^a	1.15 ^a	1.22 ^{ab}	1.29 ^b	0.073
ADG, kg/d	0.57 ^a	0.59 ^b	0.63 ^c	0.69 ^d	0.019
Feed efficiency, ⁴ gain/feed	0.472 ^a	0.466 ^a	0.488 ^b	0.552 ^b	0.02
Hip width change, cm	4.1	4.0	3.9	4.3	0.17
BCS change	0.2 ^a	0.2 ^a	0.3 ^b	0.3 ^b	0.04
Fecal score ⁵	2.2 ^a	2.2 ^a	2.2 ^a	2.3 ^b	0.01
Abnormal fecal days ⁶	0.2 ^a	0.3 ^a	0.5 ^b	0.5 ^b	0.16
Medical days ⁷	0.5	0.4	0.6	0.5	0.20

^{a-d}Means with different superscripts within a row differ ($P < 0.05$).

¹Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

²1 to 5 point scale (modified from Wildman et al., 1982).

³Average intake from 0 to 56 d.

⁴Total BW gain/(MR + starter intake).

⁵1 to 5 point scale with: 1 = normal, thick; 2 = normal, less thick; 3 = abnormal, like pancake batter; 4 = abnormal, watery with color; 5 = abnormal, watery with little to no color.

⁶Days with fecal scores >2.

⁷Days with antibiotic treatments for fever and lethargy, not including electrolytes.

Figure 6. Calf ADG increased linearly as milk replacer intake increased from d 1 to 35 for ad lib program. ADG, kg/d = $-0.017 (\pm 0.1862) + 0.709 (\pm 0.167)$ kg of DM/d (intercept, $P = 0.93$; slope, $P < 0.001$; $R^2 = 0.42$; solid line). Ad lib was ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only.

petitive compared with calves fed ad libitum milk, evident from longer standing time and more displacements at the feeder. Additionally, Rosenberger et al. (2017) suggested more unrewarded visits to automated feeders with a 6-L/d allotment compared with allotments of 8, 10, and 12 L/d indicated hunger in calves. The ear-tag sensor system employed in the current study did not record unrewarded visits but did record various activities on a continuous basis. Activities of calves on the 0.6 kg program were not elevated during the time of feeding MR compared with other treatments, possibly indicating no differences in hunger or frustration among

calves fed different MR allotments even early in the MR feeding period. However, hand-fed calves were likely conditioned to anticipate feeding, and accelerometer-based measurements may not be correlative to negative affective states such as hunger. Additionally, individually housed calves fed lesser amounts of milk or MR may not have increased activity due to hunger. Duve et al. (2012) found play behavior was significantly lower for calves housed individually and fed 5 L of milk/d compared with individually housed calves fed 9 L/d or pair-housed calves fed 5 or 9 L/d. However, differences due to treatment were only observed during wk 3 of the

Table 3. Performance of calves previously fed 4 milk replacer programs¹ during the grower phase (56 to 112 d)

Item	0.6 kg	0.8 kg	1.1 kg	Ad lib	SEM
Final BW, kg	131.5	129.0	131.2	133.7	6.42
Final hip width, cm	26.4	25.7	26.1	25.8	0.68
Final BCS	2.6 ^a	2.6 ^a	2.6 ^a	2.8 ^b	0.10
DMI, kg/d	2.98	2.90	2.90	3.11	0.103
DMI, % BW	2.96	2.87	2.80	2.92	0.064
ADG, kg/d	1.05 ^a	1.01 ^{ab}	0.98 ^b	0.98 ^b	0.023
Feed efficiency, gain/feed	0.332 ^a	0.331 ^a	0.325 ^a	0.304 ^b	0.0079
Hip width change, cm	5.4 ^a	4.9 ^b	4.8 ^b	4.6 ^b	0.14
BCS change	0.3	0.3	0.3	0.4	0.04

^{a,b}Means with different superscripts within a row differ ($P < 0.05$).
¹Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

Figure 7. Average duration spent ruminating, eating, not active, and active for calves fed 4 milk replacer programs over the nursery phase. SEM = 1.7 min/h for ruminating, 0.9 min/h for eating, 2.8 min/h for not active, and 2.1 min/h for active. Time ruminating, not active, and active changed ($P < 0.01$) with day. We found no differences among feeding programs. Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

trial and duration of play behavior declined with age (Duve et al., 2012). Therefore, it is unclear if activity of individually housed calves alone can indicate negative affective states such as hunger or frustration.

CONCLUSIONS

Feeding more than 0.66 kg/d of DM from MR increased ADG and feed efficiency without increasing

frame growth and reduced textured starter intake from 0 to 56 d, consistent with other previous observations in the literature. However, when the carryover effect of MR feeding program (25.3, 35.3, 40.9, and 46.5 kg of DM from MR intake per calf) was evaluated through 112 d, ADG and frame growth were greatest for calves previously fed less than 0.7 kg/d of DM from MR, resulting in similar 112-d BW, hip widths, and BCS. Gradual weaning and extended time on milk replacer

Table 4. Diet digestibility and intake in calves fed 4 milk replacer programs¹ during d 52 to 56 of the nursery trial (0–56 d)

Digestibility, %	0.6 kg	0.8 kg	1.1 kg	Ad lib	SEM
DM	80.2 ^a	77.7 ^{ab}	75.5 ^{bc}	73.7 ^c	1.41
OM	81.3 ^a	79.2 ^{ab}	76.8 ^{bc}	74.7 ^c	1.49
CP	75.9	73.1	73.1	72.0	2.14
ADF	46.2 ^a	38.5 ^{ab}	33.5 ^{ab}	25.0 ^b	7.32
NDF	59.8 ^a	51.3 ^{ab}	47.5 ^{ab}	39.6 ^c	5.52
Starch	95.1	96.9	93.9	93.4	1.81
Sugar	94.4 ^a	92.9 ^{ab}	91.5 ^{ab}	89.9 ^b	1.33
Fat	83.6	77.6	81.9	76.6	3.92

^{a–c}Means with different superscripts within a row differ ($P < 0.05$).

¹Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

Table 5. Diet digestibility and intake in calves fed 4 milk replacer programs¹ during d 66 to 70 of the grower trial (56–112 d)

Digestibility, %	0.6 kg	0.8 kg	1.1 kg	Ad lib	SEM
DM	83.4 ^a	81.3 ^b	77.8 ^c	75.5 ^d	0.77
OM	84.3 ^a	83.5 ^a	79.4 ^b	77.4 ^b	0.98
CP	85.5 ^a	81.5 ^b	80.2 ^{bc}	77.4 ^c	1.60
ADF	53.4 ^a	49.8 ^a	35.9 ^b	33.4 ^b	2.62
NDF	60.6 ^a	57.9 ^a	48.4 ^b	46.2 ^b	2.78
Starch	96.7 ^{ab}	97.7 ^{ab}	95.1 ^{bc}	94.5 ^c	0.83
Sugar	96.3	96.1	95.8	95.0	1.99
Fat	87.9	84.1	83.2	82.2	2.78

^{a–d}Means with different superscripts within a row differ ($P < 0.05$).

¹Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 7 d, 1.09 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

Figure 8. Average duration spent ruminating, eating, not active, and active over a 24-h period for calves fed 4 milk replacer programs. SEM = 3.9 min/h for ruminating, 2.1 min/h for eating, 6.3 min/h for not active, and 4.7 min/h for active. Time ruminating, not active, and active changed ($P < 0.01$) with day. We found no differences among programs. Treatments were 0.66 kg for first 35 d and 0.33 kg for last 7 d fed only in the a.m. (0.6 kg); 0.66 kg for 7 d, 0.82 kg for 35 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (0.8 kg); 0.66 kg for 7 d, 0.82 kg for 21 d, 0.82 kg for 7 d, 0.33 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (1.1 kg); and ad libitum allowance for 35 d, 0.82 kg for 7 d, 0.44 kg for 4 d in a.m. only, and 0.22 kg for 3 d in a.m. only (ad lib).

was employed at the 2 highest MR allowances (up to 1.09 kg/d of DM or ad libitum allowance for 35 d) but did not support similar growth rates postweaning to those observed preweaning. Milk replacer intake for calves on ad libitum allowance was highly variable and often similar to MR intake for calves receiving 1.09 kg/d of DM from MR. Later and gradual weaning did not improve fiber or sugar digestibility 1 or 3 wk postweaning, limiting ME intake in calves fed more than 0.7 kg/d of DM from MR through the weaning transition. Rumination, eating, activity, and inactivity times in the first 55 d were not affected by feeding programs but were highly variable.

ACKNOWLEDGMENTS

This research was completely funded by Provimi (Brookville, OH).

REFERENCES

- AOAC International. 2000. Official Methods of Analysis. Vol. I 17th ed. AOAC International, Arlington, VA.
- Bach, A., M. Terré, and A. Pinto. 2013. Performance and health responses of dairy calves offered different milk replacer allowances. *J. Dairy Sci.* 96:7790–7797.
- Borderas, T. F., A. M. B. de Passillé, and J. Rushen. 2009a. Feeding behavior of calves fed small or large amounts of milk. *J. Dairy Sci.* 92:2843–2852.
- Borderas, T. F., J. Rushen, M. A. G. von Keyserlingk, and A. M. B. de Passillé. 2009b. Automated measurement of changes in feeding behavior of milk-fed calves associated with illness. *J. Dairy Sci.* 92:4549–4554.
- Burfeind, O., K. Schirmann, M. A. G. von Keyserlingk, D. M. Veira, D. M. Weary, and W. Heuwieser. 2011. Technical note: Evaluation of a system for monitoring rumination in heifers and calves. *J. Dairy Sci.* 94:426–430.
- Chapman, C. E., P. S. Erickson, J. D. Quigley, T. M. Hill, H. G. Bateman II, F. X. Suarez-Mena, and R. L. Schlotterbeck. 2016. Effect of milk replacer program on calf performance and digestion of nutrients with age of the dairy calf. *J. Dairy Sci.* 99:2740–2747.
- Cowles, K. E., R. A. White, N. L. Whitehouse, and P. S. Erickson. 2006. Growth characteristics of calves fed an intensified milk replacer regime with additional lactoferrin. *J. Dairy Sci.* 89:4835–4845.
- Davis Rincker, L. E., M. J. Vandehaar, C. A. Wolf, J. S. Liesman, L. T. Chapin, and M. S. Weber Nielsen. 2011. Effect of intensified feeding of heifer calves on growth, pubertal age, calving age, milk yield, and economics. *J. Dairy Sci.* 94:3554–3567.
- De Paula Vieira, A., V. Guesdon, A. M. De Passillé, M. A. G. von Keyserlingk, and D. M. Weary. 2008. Behavioural indicators of hunger in dairy calves. *Appl. Anim. Behav. Sci.* 109:180–189.
- Dennis, T. S., F. X. Suarez-Mena, T. M. Hill, J. D. Quigley, R. L. Schlotterbeck, and L. Hulbert. 2018. Effect of milk replacer feeding rate, age at weaning, and method of reducing milk replacer to weaning on digestion, performance, rumination, and activity in dairy calves to 4 months of age. *J. Dairy Sci.* 101:268–278.
- Deswysen, A. G., P. Dutilleul, J. P. Godfrin, and W. C. Ellis. 1993. Nycterohemeral eating and ruminating patterns in heifers fed grass

- or corn silage: analysis by finite Fourier transform. *J. Anim. Sci.* 71:2739–2747.
- Diaz, M. C., M. E. Van Amburgh, J. M. Smith, J. M. Kelsey, and E. L. Hutten. 2001. Composition of growth of Holstein calves fed milk replacer from birth to 105-kilogram body weight. *J. Dairy Sci.* 84:830–842.
- Dubois, M., K. A. Gilles, J. K. Hamilton, P. A. Rebers, and F. Smith. 1956. Colorimetric method for determination of sugars and related substances. *Anal. Chem.* 28:350–356.
- Duve, L. R., D. M. Weary, U. Halekoh, and M. B. Jensen. 2012. The effects of social contact and milk allowance on responses to handling, play, and social behavior in young dairy calves. *J. Dairy Sci.* 95:6571–6581.
- Eckert, E., H. E. Brown, K. E. Leslie, T. J. DeVries, and M. A. Steele. 2015. Weaning age affects growth, feed intake, gastrointestinal development, and behavior in Holstein calves fed an elevated plane of nutrition during the preweaning stage. *J. Dairy Sci.* 98:6315–6326.
- FASS. 2010. Guide for the Care and Use of Agricultural Animals in Research and Teaching. 3rd ed. FASS Inc., Champaign, IL.
- Funaba, M., K. Kagiya, T. Iriki, and M. Abe. 1997. Duodenal flow of microbial nitrogen estimated from urinary excretion of purine derivatives in calves after early weaning. *J. Anim. Sci.* 75:1965–1973.
- Gilliland, R. L., L. J. Bush, and J. D. Friend. 1962. Relation of ration composition to rumen development in early-weaned dairy calves with observations of ruminal parakeratosis. *J. Dairy Sci.* 45:1211–1217. [https://doi.org/10.3168/jds.S0022-0302\(58\)91161-5](https://doi.org/10.3168/jds.S0022-0302(58)91161-5).
- Gordon, J. G., and I. K. McAllister. 1970. The circadian rhythm of rumination. *J. Agric. Sci.* 74:291–297.
- Hall, M. B. 2009. Analysis of starch, including maltooligosaccharides, in animal feeds: A comparison of methods and a method recommended for AOAC collaborative study. *J. AOAC Int.* 92:42–49.
- Hill, T. M., J. M. Aldrich, R. L. Schlotterbeck, and H. G. Bateman II. 2007. Effects of the feeding rate of high protein calf milk replacers. *Prof. Anim. Sci.* 23:649–655.
- Hill, T. M., H. G. Bateman II, J. M. Aldrich, J. M. Quigley, and R. L. Schlotterbeck. 2013. Evaluation of acidified, ad libitum milk replacer programs for dairy calves. *J. Dairy Sci.* 96:3153–3162.
- Hill, T. M., H. G. Bateman II, J. M. Aldrich, and R. L. Schlotterbeck. 2009. Effect of consistency of nutrient intake from milk and milk replacer on dairy calf performance. *Prof. Anim. Sci.* 25:85–92.
- Hill, T. M., H. G. Bateman II, J. M. Aldrich, and R. L. Schlotterbeck. 2010. Effect of milk replacer program on digestion of nutrients in dairy calves. *J. Dairy Sci.* 93:1105–1115.
- Hill, T. M., H. G. Bateman II, J. M. Aldrich, and R. L. Schlotterbeck. 2012. Methods of reducing milk replacer to prepare dairy calves for weaning when large amounts of milk replacer have been fed. *Prof. Anim. Sci.* 28:332–337.
- Hill, T. M., H. G. Bateman II, J. M. Aldrich, R. L. Schlotterbeck, and K. G. Tanan. 2008. Optimal concentrations of lysine, methionine, and threonine in milk replacers for calves less than five weeks of age. *J. Dairy Sci.* 91:2433–2442.
- Hill, T. M., J. D. Quigley, H. G. Bateman II, J. M. Aldrich, and R. L. Schlotterbeck. 2016a. Effect of milk replacer feeding rate and functional fatty acids on dairy calf performance and digestion of nutrients. *J. Dairy Sci.* 99:6352–6361.
- Hill, T. M., J. D. Quigley, H. G. Bateman II, F. X. Suarez-Mena, T. S. Dennis, and R. L. Schlotterbeck. 2016b. Effect of milk replacer program on calf performance and digestion of nutrients in dairy calves to 4 months of age. *J. Dairy Sci.* 99:8103–8110.
- Hill, T. M., F. X. Suarez-Mena, W. Hu, T. S. Dennis, R. L. Schlotterbeck, and L. E. Hulbert. 2017. Technical note: Evaluation of an ear-attached movement sensor to record rumination, eating, and activity behaviors in one-month old calves. *Prof. Anim. Sci.* 33:743–747.
- Hill, T. M., M. J. VandeHaar, L. M. Sordillo, D. R. Catherman, H. G. Bateman II, and R. L. Schlotterbeck. 2011. Fatty acid intake alters growth and immunity of milk-fed calves. *J. Dairy Sci.* 94:3936–3948.
- Kertz, A. F., and H. Chester-Jones. 2004. Invited review: Guidelines for measuring and reporting calf and heifer experimental data. *J. Dairy Sci.* 87:3577–3580.
- Khan, M. A., D. M. Weary, and M. A. von Keyserlingk. 2011. Hay intake improves performance and rumen development of calves fed higher quantities of milk. *J. Dairy Sci.* 94:3547–3553.
- Kiezebrink, D. J., A. M. Edwards, T. C. Wright, J. P. Cant, and V. R. Osborne. 2015. Effect of enhanced whole-milk feeding in calves on subsequent first-lactation performance. *J. Dairy Sci.* 98:349–356.
- Korst, M., C. Koch, J. Kesser, U. Müller, F. J. Romberg, J. Rehage, K. Eder, and H. Sauerwein. 2017. Different milk feeding intensities during the first 4 weeks of rearing in dairy calves: Part 1: Effects on performance and production from birth over the first lactation. *J. Dairy Sci.* 100:3096–3108.
- Meale, S. J., L. N. Leal, J. Martín-Tereso, and M. A. Steele. 2015. Delayed weaning of Holstein bull calves fed an elevated plane of nutrition impacts feed intake, growth and potential markers of gastrointestinal development. *Anim. Feed Sci. Technol.* 209:268–273.
- Miller-Cushon, E. K., R. Bergeron, K. E. Leslie, and T. J. DeVries. 2013. Effect of milk feeding level on development of feeding behavior in dairy calves. *J. Dairy Sci.* 96:551–564.
- Murphy, M. R., R. Baldwin, M. Ulyatt, and L. Koong. 1983. A quantitative analysis of rumination patterns. *J. Anim. Sci.* 56:1236–1240.
- NRC. 2001. Nutrient Requirements of Dairy Cattle. 7th rev. ed. Natl. Acad. Sci., Washington, DC.
- Nocek, J. E., and D. G. Braund. 1986. Performance, health, and post-weaning growth on calves fed cold, acidified milk replacer ad libitum. *J. Dairy Sci.* 69:1877–1883.
- Osorio, J. S., R. L. Wallace, D. J. Tomlinson, T. J. Earleywine, M. T. Socha, and J. K. Drackley. 2012. Effects of source of trace minerals and plane of nutrition on growth and health of transported neonatal dairy calves. *J. Dairy Sci.* 95:5831–5844.
- Robertson, J. B., and P. J. Van Soest. 1981. The Detergent System of Analysis and its Application to Human Foods. Cornell University, Ithaca, NY.
- Rosenberger, K., J. H. C. Costa, H. W. Neave, M. A. G. von Keyserlingk, and D. M. Weary. 2017. The effect of milk allowance on behavior and weight gains in dairy calves. *J. Dairy Sci.* 100:504–512.
- Swanson, E. W., and J. D. Harris Jr. 1958. Development of rumination in the young calf. *J. Dairy Sci.* 41:1768–1776.
- Sweeney, B. C., J. Rushen, D. M. Weary, and A. M. de Passillé. 2010. Duration of weaning, starter intake, and weight gain of dairy calves fed large amounts of milk. *J. Dairy Sci.* 93:148–152.
- Terré, M., M. Devant, and A. Bach. 2006. Performance and nitrogen metabolism of calves fed conventionally or following an enhanced-growth feeding program during the preweaning period. *Livest. Sci.* 105:109–119.
- Terré, M., M. Devant, and A. Bach. 2007. Effect of level of milk replacer fed to Holstein calves on performance during the preweaning period and starter digestibility at weaning. *Livest. Sci.* 110:82–88.
- Van Keulen, J. V., and B. A. Young. 1977. Evaluation of acid insoluble ash as a natural marker in ruminant digestibility studies. *J. Anim. Sci.* 44:282–287.
- Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, non-starch polysaccharides in relation to animal nutrition. *J. Dairy Sci.* 74:3583–3597.
- Wildman, E. E., G. M. Jones, P. E. Wagner, R. L. Boman, H. F. Trout Jr., and T. N. Lesch. 1982. A dairy cow body condition scoring system and its relationship to selected production characteristics. *J. Dairy Sci.* 65:495–501.
- Yunta, C., M. Terré, and A. Bach. 2015. Short- and medium-term changes in performance and metabolism of dairy calves offered different amounts of milk replacers. *Livest. Sci.* 181:249–255.