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# Postweaning response on growth and nutrient digestion to using different weaning strategies when feeding moderate and high amounts of milk replacer to Holstein calves

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## ABSTRACT

Many changes occur in the rumen as calves transition from consuming a liquid diet to a completely solid diet. These changes can influence growth and calf health, being greatly affected by preweaning diet as well as the transitional steps used to wean calves. A 2 × 2 factorial design of moderate [MOD; 0.66 kg of dry matter (DM)] or high (HI; up to 1.1 kg of DM) feeding rates of milk replacer (MR) and abrupt (AB; 7-d step-down) or gradual weaning (GR; 21-d step-down) was used to study how preweaning program affects calf performance from 2 to 4 mo of age. Calves (n = 50) were randomly assigned to 1 of the 4 preweaning treatments. For the following 56-d grower portion of the experiment, calves were grouped into 12 pens based on MR program, with 4 to 5 calves per pen. Data were analyzed as a completely randomized design, with repeated measures when applicable, by PROC MIXED in SAS (version 9.4; SAS Institute Inc., Cary, NC). All calves received ad libitum access to water and a textured starter [42% starch and 20% crude protein (CP)] blended with 5% chopped grass hay. Overall, apparent digestibility coefficients (dC) of DM, neutral detergent fiber, and acid detergent fiber were greater for MOD compared with HI, and apparent dC of DM and ADF were greater for GR than for AB. No significant differences were detected between organic matter, CP, fat, starch, or sugar dC based on treatment, and no interactions were observed. However, by d 56 only starch dC differed by treatment. Weaning body weight (BW), hip width (HW), and hip height (HH) were greater for HI compared with MOD calves. Weaning HH was greater for AB than for GR calves. However, final BW, HW, HH, and body condition score, as well as average daily gain, did not differ among treatments. An interaction occurred where feed efficiency (gain/feed) was reduced with GR weaning in MOD, whereas the opposite occurred in the HI group. When feeding calves a moderate level of MR, a several-step gradual weaning is not necessary to ensure growth and development; however, calves should be gradually weaned when offered a high level of MR.

**Key words:** calves, postweaning, digestibility, growth

## INTRODUCTION

There is an increasing interest in the amount of milk or milk replacer (**MR**) that should be fed to dairy calves to ensure a healthy animal with rapid and efficient prepubertal growth. Furthermore, several studies have reported epigenetic responses linking preweaning plane of nutrition with enhanced lactation performance (Fischer et al., 2019). A concern about feeding calves large quantities for milk or MR is that the intensified preweaning ADG and greater BW at weaning (Appleby et al., 2001; Diaz et al., 2001; Jasper and Weary, 2002) is usually lost by 4 mo of age compared with a moderate MR feeding regimen (Hill et al., 2016b,c). This has been attributed to a rudimentary rumen as a result of the lower starter consumption preweaning. Hence, calves not adequately adapted to solid feed intake exhibit slower postweaning growth (Terré et al., 2007; Hill et al., 2010, 2016c). Bach et al. (2013) reported that calves fed 8 L/d of MR (25% CP, 19% fat with 12.5% solids), had a BW at 52 d that was 3.7 kg greater than that of calves fed 6 L/d of MR. However, BW at d 73 (weaning) and d 228 were similar between the 2 MR rates.

Reports conflict regarding the effect of increased MR feeding rate on postweaning ADG. Some studies report reduced ADG (Hill et al., 2016c; Hu et al., 2019), whereas others report no short-term effects (Terré et al., 2007; Rosenberger et al., 2017). A reduction in structural growth postweaning has been reported in most studies where it was measured (Hill et al., 2016b,c). This decreased ADG and structural

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growth could be associated with the reduction in solid feed digestion. Concurrently, it has also been reported that intensive MR regimens reduce the digestion of an exclusively solid diet postweaning (Terré et al., 2007; Hill et al., 2010), not allowing all the available nutrients to be absorbed and utilized by the body for growth and development, resulting in lower BW gains and structural growth. Another factor to consider for an optimal transition during weaning is an adequate adaptation to a completely solid diet. Several studies have evaluated the effects postweaning of pairing a high-MR feeding program with gradual weaning; nonetheless, these did not report diet digestibility (Hill et al., 2007; Sweeney et al., 2010). One experiment (Hill et al., 2016c) reported that calves fed a high-MR diet and weaned gradually (step-down over 3 wk) increased postweaning digestion and growth compared with calves fed high levels of MR and weaned using a 1-wk step-down

These results suggest that increased starter consumption when calves are gradually weaned from high MR intake prepares their gastrointestinal tracts to enhance nutrient digestibility, resulting in greater overall performance. The present experiment aimed to evaluate the carryover effects of MR feeding rate and weaning strategy on growth and nutrient digestibility of weaned dairy calves to 4 mo of age. We hypothesized that gradual weaning could help mitigate the negative effects observed postweaning when high amounts of MR are offered to calves.

## MATERIALS AND METHODS

### *Pre-Trial 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 the approval of the Institutional Animal Care and Use Committee. Pre-trial data have been reported elsewhere (Klopp et al., 2019). Fifty Holstein bull calves, 2 to 3 d of age, were obtained from a single farm and transported 3.5 h to the Provimi Nurture Research Center (Brookville, OH). At the source farm, calves were housed in individual hutches with wire pens. They were fed 3 L of fresh colostrum within 1 h of birth, followed by another 3 L 12 h later. Calves then received 2 L of pasteurized whole milk twice daily until they left. Upon arrival at the Nurture Research Center, calves were sorted into individual pens (1.2 m × 2.4 m) with a rock tile-drained base, bedded with wheat straw inside the facility with no added heat, natural ventilation, and curtain sides. Calves were fed 0.66 kg of DM from MR (24.9% CP, 17.8% fat) the first p.m. and the next a.m. Then, calves were randomly assigned to 1 of 4 treatments in a 2 × 2 factorial arrangement. Treatments were moderate MR rate and abrupt (1 step-down) weaning strategy (**MOD-AB**; 0.66 kg for the first 42 d, and 0.33 kg for the last 7 d, a.m. only), moderate MR rate and gradual (2 step-down) weaning strategy (**MOD-GR**; 0.66 kg for 28 d, then 0.33 kg for 14 d, a.m. only; then 0.17 kg for 7 d, a.m. only), high MR rate and abrupt weaning strategy (**HI-AB**; 0.66 kg for 7 d, 0.82 kg for 7 d, 1.1 kg for 28 d, then 0.66 kg for the last 7 d, a.m. only), and high MR rate and gradual weaning strategy (**HI-GR**; 0.66 kg for 7 d, 0.82 kg for 7 d, 1.1 kg for 14 d, 0.66 kg for 14 d, a.m. only, then 0.33 kg for the last 7 d, a.m. only). All calves remained in individual pens with no MR consumption until d 56. The MOD treatments had 13 calves each, and the HI treatments had 12 calves each. During the preweaning phase, all calves received the same MR (25% CP, 17% fat, DM basis; 14% solids; Table 1), which was formulated with added synthetic amino acids (Hill et al., 2008a) and fatty acids (Hill et al., 2011). Milk replacer was fed in equal amounts twice daily at 0630 and 1530 h. Calves were given ad libitum access to a textured calf starter (20% CP, 42% starch, DM basis; Table 1) and water during the preweaning phase (56 d).

### *Trial Feed and Growth Measurements*

At d 56 of the preweaning phase (d 0 of the current phase), after calves spent 7 d housed individually indoors, consuming only starter (weaned on d 49), calves were moved to 12 group pens, with 4 to 5 calves per pen, 3 pens per treatment. The pens consisted of 6.5 $m^2$ of outside space with concrete pad and rock tile-drained yard and 1.35 $m^2$ of inside space bedded with wheat straw. During the postweaning phase, all calves were fed the same calf starter used during the prior trial, blended with 5% chopped grass hay (mean particle size of 2.5 cm) offered ad libitum, as well as

**Table 1.** Chemical composition of experimental feeds

| Item | MR[1] | Starter | Hay |
|---|---|---|---|
| DM, % as fed | 96.8 ± 1.10 | 87.9 ± 2.10 | 90.2 ± 2.20 |
| DM basis, % | | | |
| Ash | 6.0 ± 0.62 | 6.3 ± 0.49 | 9.8 ± 1.05 |
| CP | 24.9 ± 2.12 | 20.7 ± 2.25 | 5.8 ± 0.62 |
| Fat | 17.8 ± 1.99 | 3.5 ± 0.34 | 1.9 ± 0.24 |
| ADF | — | 7.5 ± 0.97 | 40.8 ± 0.39 |
| NDF | — | 14.2 ± 1.96 | 62.4 ± 0.69 |
| Starch | — | 42.4 ± 0.54 | 0.7 ± 0.13 |

[1]MR = milk replacer; manufactured from whey, whey protein concentrate, and animal fat, and used in the preweaning experiment (Klopp et al., 2019).

free choice water. Refusals were weighted back daily to determine DMI. Body weight and hip width (**HW**) were measured on d 0, 14, 35, and 56, and body condition was scored. Calves remained in group pens until the trial ended. This experiment took place from Jun. 7 to Aug. 2, 2017. The average temperature during the trial was 22°C, with a range of 9 to 33°C. The average humidity during this period was 80%, with a range of 25 to 100%.

### Digestibility Estimates

During the postweaning phase of the study, fecal samples were collected to estimate diet apparent digestibility coefficients (**dC**). Sampling was performed on d 10 to 14, 31 to 35, and 52 to 56 (indicated as d 14, 35, and 56), and samples were composited on an equal wet-weight basis to estimate total-tract diet digestibility, as described by Hill et al. (2016b,c). Briefly, fecal samples were collected from the ground of each pen, with care not to sample bed materials or other contaminants. Acid-insoluble ash was used as an internal marker for feed and fecal samples composited by pen (Van Keulen and Young, 1977).

### Feed and Digestibility Analyses

Every bale of grass hay and every other bag of MR and starter was sampled and composited for nutrient analysis. Feeds and feces were analyzed according to AOAC International (2000) for DM (oven method, 930.15), ash (oven method, 942.05), CP (Kjeldahl method, 988.05), fat (alkaline treatment with Roese-Gottlieb method, 932.06 for MR; diethyl ether extraction method, 2003.05, for starters and hay), NDF with ash (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

Data were analyzed as a complete randomized design with repeated measures, when applicable, to identify changes over time, using PROC MIXED in SAS (version 9.4; SAS Institute Inc., Cary, NC). A statistical model was developed for the analysis that included terms for the fixed factor of MR rate ($M_i$; i = 1, 2), weaning strategy ($S_g$; g = 1, 2), and day [$D_j$; j = 1 to 8 for BW and DMI, 1 to 4 for HW, HH, and BCS, and 1 to 3 for dC, DMI %BW, and feed efficiency (**FE**; 3 periods from d 10 to 14, 31 to 35, and 52 to 56)]; $MS_{(ig)}$ is the interaction of M and S, $DM_{(ji)}$ is the interaction of D and M, $DS_{(jg)}$ is the interaction of D and S, and $DMS_{(jig)}$ is the interaction of D, M, and S; $C_{k(ig)}$ is the random effect of calf within treatment (M and S), and $e_{igjk}$ is the residual error. The model was represented as follows:

$$Y_{igjk} = \mu + M_i + S_g + D_j + MS_{(ig)} + DM_{(ji)} + DS_{(jg)} + DMS_{(jig)} + C_{k(ig)} + e_{igjk},$$

where $Y_{igjk}$ is a continuous, dependent response variable and $\mu$ is the overall mean. Pen was the experimental unit (n = 3). Body measurements were taken individually but averaged together and analyzed based on pen. Body weight and intake data were grouped by week, and HW and BCS data were grouped by 14-d periods. The digestibility data were analyzed by individual 5-d collection periods (average measures from 5-d collection; d 10 to 14, 31 to 35, and 52 to 56) as well as overall with repeated measurements (Hill et al., 2016c). No interactions between D × M × S were significant for any of the growth performance-dependent variables and thus were not presented in tables nor discussed. In the mixed models with repeated measurements, the first-order autoregressive structure was selected as the appropriate covariance structure based on Akaike's information criterion.

We used ANOVA followed by Fisher's protected least significant difference test to evaluate the terms in the model. The *P*-values, least squares means, and standard errors of least squares means are presented in tables. Statistical significance was declared at $P \leq 0.05$ and trends discussed at $0.10 \geq P \geq 0.05$.

## RESULTS AND DISCUSSION

Chemical composition of feeds is presented in Table 1. Treatments were planned to differ mainly in MR intake rate and weaning strategy during the preweaning phase, and a common diet was offered during the postweaning phase.

### Milk Replacer Feeding Rate Effect

***Growth Performance.*** Weaning BW, HW, and hip height (**HH**) were greater for HI compared with MOD calves (Table 2). These differences are due to the treatments implemented during the preweaning phase of this trial and reported elsewhere (Klopp et al., 2019). However, final BW, HW, and HH (d 56) did not differ among treatments. We observed an MR rate trend ($P = 0.07$) for average BW, where HI calves had a greater average BW compared with MOD calves.

This could be attributed to MOD calves weighing less after weaning compared with HI calves. No differences were seen for weaning or final BCS. Change in HH ($P < 0.01$) was greater for MOD than for HI calves. This is due to MOD calves having a lower HH at the start of the postweaning phase but then the same HH as HI calves at the end of the postweaning phase, accounting for the greater overall change during this period. These results indicate that during the postweaning phase, HI calves lost their growth advantage over MOD calves, as a result of an inadequate amount of starter consumption before weaning causing an underdeveloped rumen that is not fully capable of digesting the nutrients in the starter (Khan et al., 2007a,b). This allowed the MOD calves, which were more accustomed to starter intake and likely possessed a more developed rumen (microbial establishment, papillae formation, initiation of rumination, and epithelial muscularization and vascularization; Khan et al., 2016), greater BW gain to make up the difference in BW. Dennis et al. (2018) compared the effects of MOD and HI MR and also reported no differences in final BW and HW. At the start of the trial, HI calves had greater BW compared with MOD calves, but by the end of the trial, HI calves no longer had greater BW.

No main effect differences in DMI occurred, as a percentage of BW or as kilograms per day, based on preweaning MR amount or weaning strategy during the grower phase (Table 2; $P > 0.15$). Interestingly, an interaction ($P = 0.03$) was detected for FE: it was lower for MOD calves that were weaned GR but greater for HI calves that were GR weaned. This could be because MOD-GR calves received the lowest overall amount of MR preweaning. Thus, under MOD feeding regimens, the advantage of providing more readily available nutrients is maintained through the postweaning period without the need for GR strategy (Appleby et al., 2001; Khan et al., 2007b). During the preweaning experiment (Klopp et al., 2019), HI MR had greater FE compared with MOD, and AB weaning had greater FE than GR. This could indicate that MOD MR regimens might not need to be gradually weaned for 3 wk, whereas gradual weaning provides a major advantage for HI MR regimens.

***Diet Digestibility.*** Table 3 shows the apparent dC for d 14, 35, and 56, as well as overall. Overall apparent dC of DM, NDF, and ADF were greater ($P < 0.05$) for MOD than for HI. Hill et al. (2016c) reported the same results when comparing MOD with HI MR feeding programs from 2 to 4 mo of age. This reflects increased development in the digestive tract of MOD calves, promoting nutrient digestion, including digestion of fiber. Based on our results, no significant differences occurred between OM, CP, fat, starch, or sugar apparent dC based on treatment, and no interactions were observed overall. These results suggest that calves receiving MOD amounts of MR preweaning are more adapted to consuming more complex nutrients, such as the ones present in the cell wall matrix of forages (Hill et al., 2016b; Dennis et al., 2018). This increased

**Table 2.** Postweaning growth performance of calves, as influenced by the 4 preweaning treatments

| Item | Preweaning treatment[1] | | | | SEM | *P*-value | | |
|---|---|---|---|---|---|---|---|---|
| | MOD-AB | MOD-GR | HI-AB | HI-GR | | Rate | Weaning | Rate × Weaning |
| Weaning BW, kg | 75.0 | 73.5 | 80.6 | 77.2 | 1.92 | 0.04 | 0.24 | 0.62 |
| Final BW, kg | 133 | 130 | 135 | 133 | 3.33 | 0.44 | 0.51 | 0.71 |
| Average BW, kg | 99.92 | 98.75 | 105.92 | 102.74 | 2.44 | 0.07 | 0.40 | 0.69 |
| Weaning hip width, cm | 20.9 | 20.8 | 21.3 | 21.3 | 0.19 | 0.03 | 0.67 | 0.93 |
| Final hip width, cm | 25.9 | 25.7 | 25.9 | 26.4 | 0.2 | 0.11 | 0.53 | 0.18 |
| Weaning hip height, cm | 83.0 | 81.1 | 84.9 | 83.0 | 0.68 | 0.02 | 0.02 | 0.96 |
| Final hip height, cm | 95.3 | 94.1 | 95.3 | 94.1 | 0.72 | 0.95 | 0.13 | 0.98 |
| Weaning BCS | 2.20 | 2.30 | 2.30 | 2.30 | 0.04 | 0.26 | 0.26 | 0.26 |
| Final BCS | 2.70 | 2.73 | 2.67 | 2.73 | 0.10 | 0.87 | 0.62 | 0.87 |
| Overall DMI, % BW | 3.01 | 3.20 | 2.98 | 2.92 | 0.10 | 0.15 | 0.53 | 0.25 |
| Overall ADG, kg/d | 1.04 | 1.01 | 0.97 | 1.01 | 0.03 | 0.33 | 0.94 | 0.25 |
| Overall feed efficiency[2] | 0.33 | 0.31 | 0.30 | 0.33 | 0.01 | 0.61 | 0.95 | 0.03 |
| Hip width change, cm | 5.00 | 5.00 | 4.60 | 5.03 | 0.19 | 0.36 | 0.29 | 0.29 |
| Hip height change, cm | 12.3 | 13.0 | 10.4 | 11.1 | 0.36 | <0.01 | 0.08 | 0.89 |
| BCS change | 0.50 | 0.47 | 0.33 | 0.47 | 0.08 | 0.34 | 0.56 | 0.34 |

[1]Calves assigned to the moderate milk replacer (MR), abrupt weaning group, MOD-AB (n = 3), were fed 0.66 kg (DM basis) of MR for the first 42 d, then 0.33 kg for the last 7 d. The moderate MR, gradual weaning group, MOD-GR (n = 3), were fed 0.66 kg of MR for 28 d, 0.33 kg for 14 d, and 0.17 kg for the last 7 d. The high MR, abrupt weaning group, HI-AB (n = 3), were fed 0.66 kg of MR for 7 d, 0.82 kg for 7 d, 1.1 kg for 28 d, and 0.66 kg for the last 7 d. The high MR, gradual weaning group, HI-GR (n = 3), were fed 0.66 kg of MR for 7 d, 0.82 kg for 7 d, 1.1 kg for 14 d, 0.66 kg for 14 d, and 0.33 kg for the last 7 d.

[2]BW gain divided by DMI.

**Table 3.** Postweaning apparent digestibility coefficients (dC) of nutrients in calves as influenced by the 4 preweaning treatments

| | Preweaning treatments[1] | | | | | *P*-value | | |
|---|---|---|---|---|---|---|---|---|
| Digestibility, % | MOD-AB | MOD-GR | HI-AB | HI-GR | SEM | Rate | Weaning | Rate × Weaning |
| d 14 Postweaning | | | | | | | | |
| DM | 83.6 | 83.3 | 81.2 | 80.5 | 0.39 | <0.01 | 0.26 | 0.65 |
| OM | 85.3 | 85.2 | 85.4 | 83.4 | 0.71 | 0.27 | 0.18 | 0.23 |
| NDF | 57.7 | 56.5 | 50.4 | 48.8 | 2.49 | 0.02 | 0.60 | 0.94 |
| ADF | 56.1 | 55.1 | 47.8 | 49.0 | 2.68 | 0.03 | 0.96 | 0.69 |
| CP | 84.1 | 84.0 | 85.0 | 83.8 | 0.83 | 0.68 | 0.43 | 0.53 |
| Fat | 80.2 | 81.9 | 81.8 | 82.4 | 1.31 | 0.45 | 0.40 | 0.68 |
| Starch | 97.7 | 97.7 | 98.0 | 95.6 | 1.09 | 0.43 | 0.30 | 0.31 |
| Sugar | 97.8 | 97.3 | 97.7 | 94.8 | 1.12 | 0.28 | 0.17 | 0.30 |
| d 35 Postweaning | | | | | | | | |
| DM | 83.0 | 84.0 | 78.5 | 83.3 | 0.54 | <0.01 | <0.01 | 0.01 |
| OM | 85.3 | 85.5 | 81.7 | 86.0 | 1.04 | 0.17 | 0.06 | 0.09 |
| NDF | 58.1 | 61.3 | 48.0 | 55.6 | 2.57 | 0.02 | 0.07 | 0.42 |
| ADF | 56.9 | 61.3 | 40.3 | 56.0 | 2.86 | 0.01 | 0.01 | 0.09 |
| CP | 84.6 | 83.4 | 80.6 | 85.5 | 1.10 | 0.40 | 0.12 | 0.02 |
| Fat | 87.7 | 87.9 | 85.1 | 87.5 | 1.47 | 0.33 | 0.42 | 0.47 |
| Starch | 96.7 | 97.3 | 94.9 | 97.0 | 0.66 | 0.17 | 0.07 | 0.27 |
| Sugar | 97.2 | 96.9 | 93.7 | 96.8 | 0.64 | 0.02 | 0.06 | 0.03 |
| d 56 Postweaning | | | | | | | | |
| DM | 80.3 | 81.0 | 81.2 | 81.3 | 0.79 | 0.46 | 0.59 | 0.74 |
| OM | 81.4 | 82.3 | 82.6 | 82.9 | 0.88 | 0.32 | 0.51 | 0.77 |
| NDF | 51.6 | 53.0 | 52.1 | 52.2 | 2.27 | 0.95 | 0.75 | 0.78 |
| ADF | 50.6 | 51.8 | 51.1 | 51.5 | 2.21 | 0.98 | 0.74 | 0.85 |
| CP | 82.5 | 81.8 | 82.9 | 83.5 | 0.76 | 0.23 | 0.90 | 0.42 |
| Fat | 82.2 | 82.8 | 84.9 | 85.6 | 1.23 | 0.06 | 0.60 | 0.98 |
| Starch | 93.8 | 96.1 | 95.4 | 97.2 | 0.55 | 0.04 | 0.01 | 0.63 |
| Sugar | 94.7 | 94.6 | 96.1 | 97.3 | 1.17 | 0.11 | 0.68 | 0.59 |
| Combined | | | | | | | | |
| DM | 82.3 | 82.8 | 80.3 | 81.7 | 0.35 | <0.01 | 0.01 | 0.16 |
| OM | 84.0 | 84.3 | 83.2 | 84.1 | 0.61 | 0.44 | 0.34 | 0.66 |
| NDF | 55.8 | 56.9 | 50.2 | 52.2 | 1.44 | 0.01 | 0.30 | 0.76 |
| ADF | 54.5 | 56.1 | 46.4 | 52.2 | 1.50 | <0.01 | 0.02 | 0.17 |
| CP | 83.8 | 83.1 | 82.8 | 84.2 | 0.71 | 0.86 | 0.62 | 0.18 |
| Fat | 83.4 | 84.2 | 83.9 | 85.1 | 0.82 | 0.39 | 0.25 | 0.82 |
| Starch | 96.0 | 97.0 | 96.1 | 96.6 | 0.55 | 0.77 | 0.22 | 0.69 |
| Sugar | 96.6 | 96.3 | 95.8 | 96.3 | 0.63 | 0.60 | 0.90 | 0.55 |

[1]Calves assigned to the moderate milk replacer (MR), abrupt weaning group, MOD-AB (n = 3), were fed 0.66 kg (DM basis) of MR for the first 42 d, then 0.33 kg for the last 7 d. The moderate MR, gradual weaning group, MOD-GR (n = 3), were fed 0.66 kg of MR for 28 d, 0.33 kg for 14 d, and 0.17 kg for the last 7 d. The high MR, abrupt weaning group, HI-AB (n = 3), were fed 0.66 kg of MR for 7 d, 0.82 kg for 7 d, 1.1 kg for 28 d, and 0.66 kg for the last 7 d. The high MR, gradual weaning group, HI-GR (n = 3), were fed 0.66 kg of MR for 7 d, 0.82 kg for 7 d, 1.1 kg for 14 d, 0.66 kg for 14 d, and 0.33 kg for the last 7 d.

nutrient digestion allowed MOD calves to converge the BW and structural growth gap with HI calves by 56 d postweaning.

At d 14 and 35, apparent dC of DM, NDF, and ADF were greater ($P < 0.05$) for MOD than for HI calves (Table 3). Hill et al. (2016c) measured digestibility on d 21 postweaning and reported greater NDF and ADF dC in MOD compared with HI, and a trend for greater DM dC in MOD calves. The lower digestibility but higher FE seen in HI calves could be explained by gut fill, leading to increased ADG but not structural growth (Hill et al., 2016c). Dennis et al. (2018) also reported increased dC of DM, NDF, and ADF for MOD compared with HI calves at d 35 postweaning. Calves fed high amounts of MR preweaning do not have an adequately developed rumen (lesser establishment of the microbiome, papillae formation, and muscularization and vascularization of the rumen wall) to effectively digest the nutrients found in starter, causing them to have lower DM, NDF, and ADF dC up to 6 wk postweaning (weaned on d 49). We detected no other differences in digestibility at d 14. At d 35 postweaning, apparent dC of sugar ($P = 0.02$) was greater for MOD than for HI. An interaction was also observed between MR feeding rate and weaning strategy for apparent dC of DM, CP, and sugar ($P < 0.05$). The combination of HI MR with GR weaning seems to drastically improve nutrient digestion compared with HI MR and AB weaning. This indicates that the combination of feeding calves increased amounts of MR and then gradually reducing it until weaning both promotes the growth of the animal preweaning and adequately prepares the rumen for solid feed consumption (Khan et al., 2007b). Apparent dC of all reported nutrients for HI-AB appears to be less than the other 3 treatments. At d 56, apparent dC for starch was greater for HI compared with MOD ($P = 0.04$). Dennis et al. (2018) also observed increased starch digestion in high-MR regimens compared with moderate at d 56 of the postweaning phase. No other differences or interactions were reported. Calves receiving HI MR were initially reported to have lower dC for DM, NDF, and ADF compared with MOD calves until d 35. Chapman et al. (2016) also reported lower dC postweaning in calves fed an increased amount of MR, which resulted in reduced ADG and structural growth. However, by the end of 56 d, no differences were seen for nutrient apparent dC except for starch, which was greater for HI than for MOD MR.

During the 56 d of this study, DM, NDF, and ADF overall digestibility were greater for MOD than for HI calves. Moreover, looking at individual sampling times, DM, NDF, and ADF dC were greater for MOD than HI calves for d 14 and 35, but no significant differences were observed in the last sampling period (d 56; Table 3), indicating that all calves were adapted to solid feed consumption (Hill et al., 2016c; Dennis et al., 2018). The DM apparent dC was greater for MOD than for HI calves over the entire 56-d postweaning period. We detected no significant difference in starch digestibility based on MR feeding rate overall, at d 14 or 35, but at d 56 starch apparent dC was significantly greater for HI than for MOD calves. By the end of the postweaning phase, HI calves were able to adapt to solid feed consumption, allowing their rumens to develop and increasing nutrient digestibility. This is evidenced by MOD calves no longer having greater dC for any nutrient at d 56 and HI calves having greater starch dC compared with MOD, indicating that MR effect on diet digestibility is lost by 4 mo of age.

### Weaning Strategy Effect

***Growth Performance.*** Only weaning HH was greater for AB than GR calves ($P = 0.02$; Table 2). These differences are due to the treatments implemented during the preweaning phase. This is likely because AB-weaned calves received MR at higher amounts for longer compared with GR, leading to increased structural growth. However, final HH based on weaning strategy was not different. Even though calves weaned abruptly consumed more MR and had increased structural growth, they may not have been adequately adapted to solid feed consumption, causing their structural growth advantage to be lost postweaning. Khan et al. (2007b) compared how conventional (reduced milk and abrupt weaning) and step-down (increased milk and gradual weaning) feeding methods affected structural growth. They reported that both at weaning (d 49) and after weaning (d 63), step-down had increased HH compared with conventional. This differed from our results and could be due to our study having a HI and MOD MR amount offered with AB and GR weaning, whereas in the study by Khan and colleagues, calves only had a moderate level of milk with abrupt weaning (10% of BW for 44 d) and a high level of milk with gradual weaning (20% of BW for 23 d, reduced over 5 d, and then 10% of BW for 16 d). No other differences were detected between weaning methods in the present study. Final BW, HW, and HH did not differ among treatments. However, the advantages seen at weaning (greater ADG, BW, and FE; Klopp et al., 2019) were lost, and all calves are the same in BW and structural growth by d 56 of the experiment (Dennis et al., 2018).

***Diet Digestibility.*** Table 3 shows the apparent dC for d 14, 35, and 56, as well as these measurements combined, to identify digestibility differences over the entire 56-d postweaning phase and by sampling period. At d 14, no dC differences were detected between AB and GR weaning for NDF or ADF. Hill et al. (2016c) also reported no differences in NDF or ADF based on a more abruptly weaned and a more gradually weaned treatment at d 14, indicating that, early in the postweaning phase, weaning strategy did not help stimulate rumen development enough to increase fiber digestion. At d 35, apparent dC of DM and ADF were greater for GR than for AB. The same increase in ADF dC for gradual compared with abrupt weaning was reported by Dennis et al. (2018) at d 35. This shift from no differences seen in ADF dC at d 14 to greater ADF dC in GR compared with AB at d 35 could be the result of cellulolytic bacteria within the rumen taking a longer time to establish (Anderson et al., 1987), causing GR weaning to have a delayed increase in ADF dC. At d 56, apparent dC for starch was greater for GR than for AB weaning ($P = 0.01$). Again, this transition, from no differences seen initially (d 14 and 35) in starch dC to greater starch dC in GR compared with AB weaning at d 56, indicates that gradual weaning has a positive carryover effect on dC for both structural and nonstructural carbohydrates. The only differences seen over the entire 56 d were greater DM and ADF dC for GR than for AB. This indicates that gradual weaning can have a positive influence on nutrient digestion by promoting starter consumption and stimulating rumen development before weaning, better preparing the animal to transition to solid fed digestion after weaning.

## CONCLUSIONS

Evaluating postweaning responses to milk replacer amount and weaning strategy revealed that gradual weaning is significantly effective when used to transition calves on a high milk replacer regimen. Postweaning, we observed that the increased growth parameters seen before weaning lasted through d 35 (~91 d of age), but all treatments converged by d 56 of the study (~112 d of age). No significant differences were detected for ADG, final BW, final hip height, final hip width, or final BCS based on milk replacer amount or weaning strategy by d 56 (~112 d of age). This confirms our hypothesis that calves fed high levels of MR would experience less growth postweaning than calves fed moderate MR, allowing the moderate-MR calves to reduce the growth gap by d 56 postweaning. We also found no apparent differences in digestibility coefficients at d 56 (~112 d of age) between treatments, except for starch. In conclusion, calves on a program of moderate milk replacer did not benefit from an extended weaning period of 3 wk, as in gradual weaning, compared with 1 wk as in a single-step weaning. However, when calves are administered a high amount of milk replacer, the regimen should be paired with a gradual weaning process, to ensure successful growth and development.

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