ABSTRACT

The objective of this study was to assess the effects of intake-based weaning methods and forage type on feeding behavior and growth of dairy calves. Holstein dairy calves (n = 108), housed in 12 groups of 9, were randomly assigned to 1 of 3 weaning treatments: milk reduction based on age (wean-by-age), individual dry matter intake (DMI; wean-by-intake), or a combination of individual DMI and age (wean-by-combination). Groups of calves were alternately assigned to 1 of 2 forage treatments: grass hay or a silage-based total mixed ration (TMR; n = 6 groups per treatment). Until 30 d of age, all calves were offered 12 L/d of whole milk. Starting on d 31, milk was gradually reduced by 25% of the individual’s average milk intake. For wean-by-age calves (n = 31), the milk allowance remained stable until d 62 when milk was again reduced gradually until weaning at d 70. For wean-by-intake calves (n = 35), milk allowance was reduced by a further 25% once calves consumed on average 200, 600, and (finally) 1,150 g of dry matter (DM) per day of calf starter and forage. For wean-by-combination calves (n = 35), milk intake remained stable until calves consumed on average 200 g of DM/d, at which point milk was reduced linearly until weaning at d 70. If calves failed to reach DMI targets by d 62 (n = 10), milk was then reduced gradually until weaning at d 70. Of the 35 wean-by-intake calves, 27 met all 3 DMI targets (successful-intake), and 33 of the 35 calves in the wean-by-combination treatment met the 200 g of DM/d target (successful-combination). Successful-intake and successful-combination calves had greater final body weight (BW) at 12 wk of age than wean-by-age calves (123.7 vs. 122.3 vs. 117.7 ± 3.1 kg, respectively). During weaning, successful-intake calves ate more starter and consumed less milk than successful-combination and wean-by-age calves (starter: 1.19 vs. 0.89 vs. 0.49 ± 0.07 kg of DM/d, respectively; milk: 2.7 vs. 4.2 vs. 5.9 ± 0.17 L/d, respectively). After weaning, successful-combination and successful-intake calves consumed similar amounts of starter; however, wean-by-age calves continued to consume less starter (2.85 vs. 2.78 vs. 2.44 ± 0.10 kg of DM/d, respectively). During weaning, hay and TMR calves ate similar amounts of forage, but hay calves consumed more starter (0.96 vs. 0.75 ± 0.07 kg of DM/d, respectively). After weaning, hay calves continued to consume more starter (2.88 vs. 2.50 ± 0.10 kg of DM/d, respectively), whereas TMR calves consumed more forage (0.33 vs. 0.15 ± 0.02 kg of DM/d, respectively). Hay calves had greater final BW at 84 d compared with TMR calves (124.0 vs. 119.0 ± 1.6 kg, respectively). These results show that the inclusion of a DMI target can improve starter intake and BW for calves that successfully wean, and that forage type can influence the transition onto solid feed. We also found that approximately 10% of calves failed to consume even 200 g of DM/d by 9 wk of age; more research is needed to better understand why some calves struggle to transition onto solid feed.

Key words: precision farming, robotic milk feeders, individualized weaning, animal welfare

INTRODUCTION

Dairy calves are often fed restricted allowances of milk (approximately 4–6 L/d) (USDA, 2016; Medrano-Galarza et al., 2017). Providing calves higher allowances of milk (e.g., 10–12 L/d) reduces signs of hunger, increases growth (e.g., Jensen and Holm, 2003; Khan et al., 2007b), and results in increased productivity later in life (Heinrichs and Heinrichs, 2011; Soberon et al., 2012). However, calves fed high allowances of milk typically have low solid feed intake before weaning (Rosenberger et al., 2017), increasing hunger and slowing weight gains when milk is abruptly removed (de Passillé et al., 2011; Dennis et al., 2018).

Gradual weaning can improve starter intake before milk is completely withdrawn. Step-down (e.g., Khan et al., 2007b) and linear (e.g., Sweeney et al., 2010) reductions in milk allowances have been investigated, but
the majority of studies have used age as the criterion for when milk allowances are reduced. However, there is considerable variability in when calves begin to consume solid feed (Heinrichs and Heinrichs, 2011; Neave et al., 2018), and some calves may not consume much starter before they reach a certain age. Another approach is to wean calves when they meet a starter intake target, with the idea that calves are then nutritionally ready to transition to solid feed (Roth et al., 2009; de Passillé and Rushen, 2012, 2016). This method can also allow for the reallocation of milk from calves that wean early to calves that need more time to transition onto solid feed (Benetton et al., 2019). Weaning by starter intake can result in intermediate weaning ages (de Passillé and Rushen, 2012), reduced milk intake, increased starter intake, and similar postweaning weights compared with calves gradually weaned at a set age (Benetton et al., 2019).

One disadvantage of weaning based on starter intake is that calves show a higher number of unrewarded visits to the milk feeder during the weaning period (10–15 times a day versus just 5 times a day for calves weaned by age: de Passillé and Rushen, 2012; Benetton et al., 2019). A high number of unrewarded visits is considered a sign of hunger (De Paula Vieira et al., 2008; Nielsen et al., 2008), specifically a sign of hunger for milk rather than low energy intake (de Passillé and Rushen, 2012). A drawback of previous studies is that when calves reached specific targets for starter intake, milk allowances were reduced abruptly (de Passillé and Rushen, 2016; Benetton et al., 2019). Additionally, if calves responded to reduced milk allowance by immediately increasing their starter intake, this would trigger a further abrupt reduction in milk allowance such that some calves were fully weaned within one week. Previous studies have also reported that approximately 18% of calves fail to meet starter intake targets by a predetermined age (de Passillé and Rushen, 2012; Benetton et al., 2019; Whalin et al., 2022). Thus, further refinements to weaning programs based on individual solid feed intake are needed, perhaps by reducing the milk more gradually once a solid feed intake target is reached.

Forage provision is another important consideration in early calf feeding programs. Recent work has shown that providing forage to calves fed high milk allowances before weaning improves overall solid feed intake, promotes rumen development, and increases rumen pH (Khan et al., 2011a; Laarman et al., 2012). One area of recent interest is incorporating silages, such as a lactating cow TMR, into a pre-weaning calf diet (Overvest et al., 2016; Mirzaei et al., 2017). Silages may provide a palatable forage source that encourages solid feed intake and rumen development (Kehoe et al., 2021). In addition, offering a lactating cow TMR could also act as a supplementary source of grain intake, aiding calves that struggle to transition onto calf starters. Currently, there has been little work exploring behavior and performance of dairy calves fed dry forages versus silages around weaning.

The use of automated calf feeders and solid feed intake as a criterion for weaning has increased in North America (USDA, 2016; Medrano-Galarza et al., 2017). Despite increases in use of solid feed intake as a weaning criterion, little is understood about the best practices for weaning calves this way. The first objective of this study was to evaluate feed intake, feeding behavior, and growth of calves weaned by age, by individual DMI, and by a combination of individual DMI and age. We tested an age-based weaning method because this is still the most common criterion to wean calves (USDA, 2016). We tested an intake-based method similar to that of Benetton et al. (2019) but added a gradual reduction in milk allowances over a 3-d period after calves met intake targets, to eliminate abrupt drops in milk. Finally, we tested a combination of the intake and age methods, involving small incremental reductions in milk over a longer period but only after meeting an initial DMI target; we expected this method to reduce the large number of unrewarded visits when calves are weaned based on intake alone. Overall, we expected intake-based weaning methods to encourage greater solid feed intake during weaning, resulting in greater solid feed intake after weaning and overall growth. We also anticipated that a proportion of calves assigned to the intake-based weaning methods would fail to meet intake targets based on previous work (see de Passillé and Rushen, 2012; Benetton et al., 2019; Whalin et al., 2022).

Our second objective was to explore the effects of providing forage as either grass hay or a silage-based TMR on feeding behavior and growth of calves on different weaning programs. We expected that calves fed the silage-based TMR would have greater forage consumption, resulting in greater total DMI and improved growth compared with calves fed grass hay.

MATERIALS AND METHODS

This experiment was conducted from August 2019 to September 2020 at The University of British Columbia (UBC) Dairy Education and Research Centre in Agassiz, BC, Canada. The animals were cared for according to the guidelines of the Canadian Council of Animal Care (2009), with animal use approved by the UBC Animal Care Committee (protocol no. A19-0152).
**Animals and Housing Management**

This experiment used 108 Holstein calves (n = 86 females; n = 22 males) with an average birth weight of 41.2 ± 5.5 kg (mean ± SD). After separation from the dam (within 6 h after birth), calves were placed in an individual pen bedded with sawdust, and bottle fed 4 L of colostrum (>50 g/L of IgG). If less than 3 L of colostrum was consumed, calves were tube fed the remaining amount (n = 32). On average calves consumed 3.9 ± 0.3 L (mean ± SD) of colostrum. A blood sample was collected from the jugular vein at 24 h to 48 h after the first feeding of colostrum, and the serum was analyzed using a Reichert AR 200 Digital Hand-Held Refractometer (Reichert Technologies). All calves had serum total protein levels >5.2 g/dL (as recommended for passive transfer of immunity; Windeyer et al., 2014). While individually housed, calves were bottle fed 8 L/d of whole milk divided into 2 feedings daily. At 2 d of age calves were moved into sawdust-bedded group pens (4.9 × 7.3 m) containing 9 calves each. Calves were moved into group pens in chronological order according to their birth date until 108 calves (12 groups, 9 calves per group pen) were enrolled. Within each group pen, calves were enrolled within 13.9 ± 4.9 d of each other. Calves remained in the group pen until the youngest calf of the group completed the experimental period (84 d of age).

**Preweaning Diet and Forage Treatments**

Until 30 d of age all calves had access to 12 L/d of pasteurized whole milk, fed at 40°C using automated feeders (CF 1000 CS Combi; Delaval Inc.). Each pen had a milk feeder equipped with 1 teat and barriers (0.4 × 1.5 m) that restricted access to a single calf. Milk allowances accumulated at a rate of 5% of the daily allowance every hour from midnight to 2000 h, and the milk feeder delivered a minimum of 0.5 L and a maximum of 9.5 L per visit. Calves were able to split their accumulated milk allowance into as many visits as desired, but calves received milk (i.e., the feeder visit was rewarded) only if the minimum milk allocation had accrued. Daily milk intake and the number of unrewarded visits (i.e., when calves entered the feeder but were not allowed to drink milk) were automatically recorded by the milk feeder, using radio frequency identification ear tags to individually identify calves. After weaning, continued visits to the milk feeder (by definition, unrewarded) were still recorded. Adjacent to the milk feeder was a starter feeder, also equipped with a barrier (0.4 × 1.0 m) to restrict access to a single calf. Milk and starter feeders were 0.5 m apart. Starter was dispensed in 20-g increments while the calf’s head was in the feeder. Daily starter intake was also recorded by the CF 1000 feeder. All calves had ad libitum access to the calf starter (20% CP texturized and consisting of (on as-is basis) 31.2% flake barley, 15.3% canola meal, 15.0% flaked corn, 12.3% soybean meal, 8.7% wheat, and 6.5% molasses (Richie Smith Feeds Inc.).

Group pens were alternately assigned to the forage treatments: grass hay or a silage-based lactating cow TMR (n = 6 groups per treatment). The hay was a local blend of tall fescue, orchard grass, and ryegrass. The TMR consisted of 32% corn silage, 14% grass silage, 6% alfalfa hay, 2% straw, and 46% concentrate mix consisting primarily of canola, soybean, and corn meal. Hay or TMR, and water were offered ad libitum from automated Insentec feeders (RIC; Insentec B.V.). For each visit to the feeder, calf number was recorded using radio frequency identification tags, and the initial and final time of visit and weight of forage were used to calculate visit duration and forage intake. Barriers (0.4 × 0.6 m) were located on each side of the feeders to restrict access to a single calf. Forage feeders were 1.6 m from the starter feeder and 2.0 m from the milk feeder. Forage was replaced twice daily at 0900 and 1800 h. As forage was fed at the group level, waste and sorting of feed was not recorded.

**Weaning Treatments**

When moved to the group pen, calves were randomly allocated (within blocks of 3 based upon calf age) to the 3 weaning treatments. Each group contained a total of 9 calves (with 3 calves in each treatment). As subsequent blocks were enrolled, we scrutinized birth weight and sex to ensure that these were similar across treatments. For calves to be eligible to begin weaning at d 31, they had to consume a minimum average milk intake of 6 L/d over the previous 5 d. If calves did not meet this criterion, they remained in the group pen but were excluded from the experiment. This criterion was applied to all weaning treatments. Additionally, if calves in the 2 intake-based weaning treatments (i.e., wean-by-intake and wean-by-combination) did not reach intake targets by d 62 of age, they were forced to wean and excluded from the analysis. All calves, regardless of treatment, experienced an initial milk reduction at d 31, following previous work employing gradual step-down weaning methods (Benetton et al., 2019). Milk allowance was gradually reduced by 25% of each individual’s average milk intake over 3 d (i.e., milk was reduced by approximately 8%/d) such that on d 33 calves were at 75% of their previous milk intake. After this initial milk reduction, calves began their assigned weaning protocol, described as follows.
Wean-By-Age. Milk allowance remained stable for the next 29 d. Starting on d 62, milk allowance was gradually reduced (again by approximately 8%/d) such that by d 70 calves were completely weaned.

Wean-By-Intake. Milk allowance was reduced (again by 25% over 3 d) once the calf achieved daily solid feed DMI targets of 200, 600, and 1,150 g of DM/d (complete weaning). These targets corresponded to the 225, 675, and 1,300 g/d of as-fed starter feed intake targets reported by Benetton et al. (2019). Dry matter was calculated and corrected on a weekly basis for starter, hay, and TMR using the microwave method described herein. Calves needed to consume the target rolling average intake across 3 d, with a daily minimum of no less than 50% of the target. If calves did not meet any target by d 62, they were weaned as described for the wean-by-age treatment. For calves that met the first DMI target but not the second, on d 65 milk allowance was gradually reduced over 6 d (again, by approximately 8%/d) so that on d 70 calves were completely weaned. For calves that met the second DMI target but not the third, on d 68 milk allowance was gradually reduced over 3 d (again by approximately 8%/d) so that on d 70 calves were completely weaned.

Wean-By-Combination. When calves met the first solid feed DMI target of 200 g of DM/d (from the wean-by-intake treatment), milk allowance was gradually reduced so that all calves were fully weaned on d 70; the rate of daily milk reduction depended on the age at which each calf met the solid feed intake target. For example, a calf that met the target at d 50 had milk reduced at a rate of 5%/d over 20 d to wean by d 70. Calves that had not reached the DMI target by d 62 were weaned as described for the wean-by-age treatment.

Growth and Health

Calves were individually weighed and health scored on a weigh scale (Smart1 Scales, Westernscale Inc.) twice per week. Health examinations followed the Wisconsin Dairy Calf Health Scoring chart (University of Wisconsin-Madison, 2015) and were scored for the purpose of controlling for illness (health was not considered an outcome measure). Body measurements were recorded as described by Khan et al. (2007a), including body barrel, heart girth, and withers height. Visual examinations were performed twice daily (a.m. and p.m.); any calf showing signs of illness was examined further following the health examination procedure described herein and treated accordingly. Milk consumption of each calf was recorded daily. During the preweaning phase, calves were assisted to the milk feeder if they failed to visit the feeder that day, or if they consumed <2 L of milk before 0900 h or <4 L of milk before 1800 h.

Calves showing signs of diarrhea (fecal score = 3; where 0 = normal, 1 = semi-formed and pasty; 2 = loose but stays on top of bedding, and 3 = watery and sifts through bedding) and low milk consumption were accompanied by fever (body temperature ≥39.5°C), were treated with an electrolytic solution for 3 d or until fecal score returned to normal; if diarrhea and low milk consumption were accompanied by fever (body temperature ≥39.5°C), these calves were also administered a non-steroidal anti-inflammatory drug (Metacam 20 mg/mL, Boehringer Ingelheim). Calves showing signs of respiratory illness, consisting of nasal discharge (when nasal score ≥2; where 0 = normal discharge, 1 = small amount of unilateral cloudy discharge, 2 = bilateral, cloudy or excessive mucus discharge, and 3 = copious bilateral mucopurulent discharge), pulmonary infection (when lung score = 2; where 0 = no lung consolidation detected, 1 = some lung consolidation, 2 = bilateral consolidation, and fever (body temperature ≥39.5°C), were treated with an antibiotic (Resflor Gold, Intervet Inc.). Calves were classified as sick if they had a score 3 or greater for diarrhea, had a score of 4 or greater for pulmonary inflammation, were treated with a non-steroidal anti-inflammatory drug or antibiotics, or had a combination of these at any point during the experiment.

Feed Sample Collection and Analysis

Weekly starter, hay, and TMR samples were collected from each group pen before calves had access to the fresh forage. Dry matter was calculated using the microwave method following Oetzel et al. (1993). Briefly, samples (approximately 100 g) were heated in a 700-W microwave oven sequentially for 1.5 min, 1 min, 45 s, 30 s, and 15 s at maximum power. Between each period, the sample was removed from the microwave, cooled for 10 s, and mixed to avoid burning. Immediately following this process, the sample weight was recorded, and the sample was heated again for 15 s. This step was repeated until the difference from the previous sample weight was <0.1 g for 3 consecutive intervals. The microwave used was equipped with a rotating plate and digital clock to determine timing. Dry matter percentage was calculated using the difference between the initial and final weight of the sample.

Milk samples were collected once per week from the milk storage tank and analyzed for components (Pacific Milk Analysis Laboratory, Chilliwack, BC, Canada). Calf starter, hay, and TMR samples were collected weekly, frozen, and pooled into 3-mo periods for nutri-
ent and DM analysis (Cumberland Valley Analytical Services, Waynesboro, PA). All automated feeders were calibrated once per week to verify accurate dispensing of milk, starter portions, and weighing of hay and TMR. Milk and solid feed nutrient analyses, as well as particle length size for forages, are reported in Table 1.

### Statistical Analysis

All statistical analyses were performed in SAS (version 9.4; SAS Institute Inc.), with calf as the experimental unit for weaning treatments and group as the experimental unit for forage treatments. Our a priori power analysis was based upon the weaning treatment, using calf as the experimental unit and unrewarded visits as the primary outcome measure. Using estimates of effect size and variance from Benetton et al. (2019), and power set at 0.8 and \( \alpha \) at 0.05, we calculated a required sample of 36 calves for each of our 3 weaning treatments. Blinding was not possible, as researchers needed to know assigned treatments to apply weaning methods and provide correct forage type. Data were scrutinized using probability distribution plots. The variable unrewarded visits preweaning was square-root transformed to normalize residuals.

Seven calves were removed from all analyses: 2 calves died (1 in the wean-by-age receiving TMR, and 1 wean-by-intake receiving TMR); 3 calves had BW at 84 d more than 3 SD lower than the mean (2 wean-by-age receiving hay, and 1 wean-by-age receiving TMR); and 2 calves failed to meet the criterion of average milk intake >6 L/d at the time of initial step-down on d 31 (1 wean-by-combination receiving TMR, and 1 wean-by-age receiving TMR).

Additionally, 10 calves failed to meet intake targets in the wean-by-intake (8 calves) and wean-by-combination (2 calves) treatments; as these calves failed to complete their assigned weaning protocol, they were removed from any inferential test of the effect of treatment, and their results are presented graphically for descriptive purposes. Previous work investigating intake-based weaning methods has also found a proportion of calves failing to reach intake targets by a predetermined age, and these failed calves were removed from their respective treatments (de Passillé and Rushen, 2012; Benetton et al., 2019; Whalin et al., 2022). A total of 91 calves remained in the present analysis: wean-by-age, \( n = 31 \); successful-intake (met all 3 intake targets), \( n = 27 \); and successful-combination (met the intake target by d 62), \( n = 33 \).

The effects of weaning treatment, forage treatment, and the weaning \( \times \) forage interaction were tested using a mixed linear regression model. Data for feed intake, feeding behavior, and growth were summarized into 3 periods: preweaning (d 2–30), weaning (d 31–69), and postweaning (d 70–84). The effects of treatment were tested separately within each period, as we had a strong expectation that these effects would differ across periods, based upon the results of previous work (Benetton et al., 2019; Whalin et al., 2022).

The following response variables were tested: feed intake (milk intake, starter DMI, forage DMI, total DMI), feeding behavior (unrewarded visits to the milk feeder), and growth (ADG, gain-to-feed ratio, rate of

### Table 1. Mean (±SD) chemical composition of milk, calf starter, hay, and TMR, and particle length size of hay and TMR (DM basis) offered to Holstein dairy calves (\( n = 108 \))

| Item         | Milk          | Calf starter | Hay          | TMR          |
|--------------|---------------|--------------|--------------|--------------|
| Chemical composition |               |              |              |              |
| DM (%)       | 12.2 ± 0.4    | 86.2 ± 0.6   | 85.2 ± 1.1   | 44.6 ± 2.9   |
| CP (%)       | 26.8 ± 1.2    | 23.7 ± 1.3   | 14.1 ± 1.0   | 16.4 ± 1.1   |
| Fat (%)      | 33.4 ± 1.1    | 5.4 ± 1.1    | 2.5 ± 0.2    | 5.5 ± 0.3    |
| Lactose (%)  | 33.2 ± 1.0    | ND           | ND           | ND           |
| NDF (%)      | ND            | 11.1 ± 0.4   | 56.4 ± 1.3   | 32.1 ± 2.2   |
| ADF (%)      | ND            | 6.0 ± 0.7    | 32.0 ± 0.8   | 20.4 ± 2.2   |
| Starch (%)   | ND            | ND           | 2.7 ± 0.1    | 23.0 ± 2.0   |
| Ash (%)      | ND            | 7.6 ± 0.6    | 7.6 ± 1.3    | 8.0 ± 0.2    |
| ME2 (Mcal/kg)| 5.1 ± 0.05    | 3.2 ± 0.08   | 2.4 ± 0.06   | 2.8 ± 0.08   |
| Particle length3 |               |              |              |              |
| Long (%)     | ND            | ND           | 58.4 ± 9.5   | 23.8 ± 7.6   |
| Medium (%)   | ND            | ND           | 20.3 ± 4.4   | 35.6 ± 5.8   |
| Short (%)    | ND            | ND           | 17.4 ± 4.4   | 27.8 ± 1.9   |
| Fine (%)     | ND            | ND           | 3.9 ± 2.4    | 12.8 ± 2.2   |

1\( ND = \text{not determined.} \)

2\( ME = TDN \times 0.04409 \times 0.82; \text{calculated according to NRC (2001) equations.} \)

3\( \text{Particles separated, using a Penn State Particle Separator, into 4 fractions: long (>19 mm), medium (<19, >8 mm), short (<8, >1.18 mm), and fine (<1.18 mm).} \)
Weaning Treatments

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for each forage treatment (i.e., hay and TMR). We also graphed weekly starter and forage intakes and BW to wean on the 2 intake-based weaning methods. We presented separately for these treatments and the interaction was found in any model, so results are ≤ 0.05 and tendencies at \( P = 0.06 \). Significance was declared at standard error for each period. Descriptive purposes, we graphed weekly milk, starter, and forage intakes, BW, and unrewarded visits to the milk feeder for each weaning treatment, as well as calves that failed to wean on the 2 intake-based weaning methods. We also graphed weekly starter and forage intakes and BW for each forage treatment (i.e., hay and TMR).

RESULTS

Weaning Treatments

Descriptive Results: Failed Calves and Age and Duration of Weaning. Within the wean-by-intake treatment, 8 calves failed to complete weaning; 3 failed to meet the first target of 200 g of DM/d, and 5 failed to meet all the remaining targets. Within the wean-by-combination treatment, 2 calves failed to meet the 200 g of DM/d target. Failed calves consumed little solid feed before wk 9, when they were force-weaned (Figure 1). During weaning, failed calves consumed on average (mean ± SD) 0.14 ± 0.06 kg of DM/d of starter and 0.05 ± 0.04 kg of DM/d of forage, showing an ADG of 0.36 ± 0.12 kg/d. After weaning, failed calves consumed 1.88 ± 0.45 kg of DM/d of starter and 0.15 ± 0.06 kg of DM/d of forage, with ADG of 1.37 kg/d. At 84 d, failed calves had a final BW of 95.3 ± 8.3 kg. After the initial step-down on d 31, the mean milk allowance for failed calves was 7.1 ± 0.8 L/d.

Successful-intake calves (i.e., calves in the wean-by-intake treatment that met all 3 intake targets) had a mean (±SD) weaning age of 56.3 ± 5.8 d (range: 48–70 d) and a weaning duration (from time to meet first target of 200 g of DM/d to complete weaning) of 16.3 ± 4.0 d (range: 12–26 d). For successful-combination calves (i.e., that met the 200 g of DM/d intake target), the duration of weaning was nearly double that of successful-intake calves (28.3 ± 6.1 d, range: 10–34 d).

Milk and Feed Intake. Before weaning, milk intakes were similar across weaning treatments (Table 2); however, we observed large individual variability in milk intakes for wean-by-age (mean: 8.7 L/d, range: 6.4–10.6 L/d), successful-intake (mean: 8.5 L/d, range: 5.4–11 L/d), and successful-combination calves (mean: 8.6 L/d, range: 6.1–10.1 L/d). Once weaning began, wean-by-age calves consumed 3.2 L/d more than successful-intake calves \((t_{1,71} = 15.7, P < 0.001)\) and 1.7 L/d more than successful-combination calves \((t_{1,71} = 8.9, P < 0.001)\).

Starter intake increased with age, especially starting after the initial milk reduction at d 31 for all weaning treatments. Successful-intake calves consumed the most starter during weaning, averaging 0.30 kg of DM/d more than successful-combination calves \((t_{1,70} = 4.0, P < 0.001)\), and 0.70 kg of DM/d more than wean-by-age calves \((t_{1,72.9} = 9.2, P < 0.001)\). As a result, successful-intake calves had the highest total DMI during weaning \((t_{1,70.3} = 21.1, P < 0.04)\). After weaning, successful-combination calves were able to catch up to successful-intake calves such that starter intakes were similar; however, wean-by-age calves continued to consume less starter than successful-intake and successful-combination calves \((t_{1,73.8} > 3.3, P < 0.001)\). Successful-intake and successful-combination calves had greater total DMI after weaning compared with wean-by-age calves \((t_{1,73.8} > 3.3, P < 0.001)\).

Unrewarded Visits. Unrewarded visits to the milk feeder increased around wk 5 for successful-intake and successful-combination treatments. Unsuccessful visits decreased after weaning, but successful-intake calves showed the fewest visits \((t_{1,71.9} > 2.6, P < 0.01)\).
Figure 1. Arithmetic means (±SE) for descriptive purposes of (A) milk intake, (B) starter intake, and (C) forage intake for Holstein calves aged 1 to 12 wk. Values are shown separately for calves in the wean-by-age (n = 31), successful-intake (n = 27), and successful-combination (n = 33) treatments. We also show calves that failed to reach intake targets in the 2 intake-based weaning treatments (n = 10). All calves received 12 L/d of milk until d 31, when milk was reduced by 25% based on individual average milk intake. Wean-by-age calves’ milk remained stable until d 62, when milk was reduced until weaning at d 70. Successful-intake calves’ milk was further reduced by 25% when calves met DMI targets of 200, 600, and 1,150 g of DM/d (including starter and forage). Successful-combination calves’ milk remained stable until calves met a DMI target of 200 g of DM/d; milk was then reduced until weaning at d 70. Failed calves were forced to wean from d 62 to 70. Groups of calves were alternately assigned to either grass hay or silage-based TMR (n = 6 groups per treatment).
**Growth.** Successful-intake and successful-combination calves had similar ADG during the weaning period and a similar final weight at d 84 (Table 3, Figure 3). However, wean-by-age calves showed reduced ADG during the weaning period compared with the other treatments \( (t_{1,74.2} < 2.2, P < 0.03) \), such that their final BW was approximately 5 kg lower at 84 d of age \( (t_{1,74.9} > 2.0, P < 0.05) \). After weaning, wean-by-age calves had a higher gain-to-feed ratio compared with successful-intake and successful-combination calves \( (t_{1,74.2} < 2.9, P < 0.004) \).

We performed a post-hoc descriptive analysis with a simple linear regression to explore differences in growth (total weight gain from 2 to 84 d of age) in relation to total accumulated starter intake over the same period. As expected, we found that total weight gain increased with total starter intake (Figure 4).

Daily growth in structural body measurements did not differ between treatments before weaning. During weaning, wean-by-age calves had reduced body barrel and heart girth growth compared with successful-intake and successful-combination calves \( (t_{1,73.2} > 2.9, P < 0.02) \). Calves generally had similar structural growth measures after weaning, except that wean-by-age calves had greater body barrel growth compared with successful-intake and successful-combination calves \( (t_{1,81.9} > 2.4, P < 0.02) \). At 84 d of age, successful-intake and successful-combination calves had similar final structural body measures, whereas wean-by-age calves had (or tended to have) reduced final body barrel and heart girth \( (t_{1,82.3} > 2.0, P < 0.06) \).

**Post-Hoc Classification of Wean-By-Age Calves.** The foregoing analysis follows our original intention of the wean-by-age treatment group, which was to reflect standard farm practice of weaning all calves based on age regardless of solid feed intake. However, the lower average BW of calves in the wean-by-age treatment group was affected by 3 calves that consumed little solid feed before the final milk reduction at d 62. Indeed, if these calves had been in the wean-by-intake or wean-by-combination treatments, they would have been classified as failed calves and removed from the analysis. We therefore tested whether the results for the wean-by-age calves were driven by the 3 calves that consumed less than 200 g of DM/d before 62 d of age (the first intake target for wean-by-intake and wean-by-combination treatments). Calves that were consuming sufficient solid feed before weaning in the wean-by-age treatment (successful-age; \( n = 28 \)) were compared with successful-intake and successful-combination. This new analysis was performed as described in the Statistical Analysis section, and results are presented in Supple-

| Response variable | Wean-by-age | Successful-intake | Successful-combination | SE | P-value |
|-------------------|-------------|-------------------|------------------------|----|---------|
| Preweaning (d 2–30) |             |                   |                        |    |         |
| Milk intake (L/d) | 8.6         | 8.5               | 8.7                    | 0.20 | 0.64    |
| Starter DMI (kg/d)| 0.023       | 0.030             | 0.024                  | 0.005 | 0.31    |
| Forage DMI (kg/d) | 0.005       | 0.006             | 0.005                  | 0.001 | 0.61    |
| Total DMI (kg/d)  | 1.03        | 1.02              | 1.03                   | 0.03 | 0.83    |
| Unrewarded visits\(^{2}\) (no./d) | 1.7 | 1.3 | 1.4 | 0.40 | 0.53 |
| Weaning (d 31–69) |             |                   |                        |    |         |
| Milk intake (L/d) | 5.9\(^{a}\) | 2.7\(^{c}\)       | 4.2\(^{b}\)            | 0.17 | <0.001  |
| Starter DMI (kg/d)| 0.49\(^{a}\) | 1.19\(^{c}\)      | 0.89\(^{b}\)          | 0.07 | <0.001  |
| Forage DMI (kg/d) | 0.08\(^{b,\text{xy}}\) | 0.12\(^{c}\) | 0.10\(^{b}\)         | 0.01 | 0.003   |
| Total DMI (kg/d)  | 1.25\(^{a}\) | 1.60\(^{c}\)       | 1.46\(^{b}\)          | 0.06 | <0.001  |
| Unrewarded visits (no./d) | 6.8\(^{b}\) | 10.2\(^{c}\) | 10.4\(^{b}\) | 0.74 | <0.001 |
| Postweaning (d 70–84) |             |                   |                        |    |         |
| Starter DMI (kg/d)| 2.44\(^{b}\) | 2.85\(^{c}\)       | 2.78\(^{a}\)          | 0.10 | <0.001  |
| Forage DMI (kg/d) | 0.24        | 0.23              | 0.24                   | 0.02 | 0.91    |
| Total DMI (kg/d)  | 2.66\(^{b}\) | 3.07\(^{c}\)       | 3.00\(^{a}\)          | 0.10 | <0.001  |
| Unrewarded visits (no./d) | 4.3\(^{b}\) | 1.4\(^{c}\) | 3.3\(^{c}\) | 0.33 | <0.001 |

\(^{a}\)Means with different superscripts within a row indicate a significant difference \( (P \leq 0.05) \) between wean-by-age, successful-intake, and successful-combination calves.

\(^{b}\)Means with different superscripts within a row indicate a tendency \( (0.05 < P \leq 0.1) \) between wean-by-age, successful-intake, and successful-combination calves.

\(^{1}\)All calves received 12 L/d of milk until d 31, when milk was reduced by 25% based on individual average milk intake. Wean-by-age calves’ milk remained stable until d 62, when milk was reduced until weaning at d 70. Successful-intake calves’ milk was further reduced by 25% when calves met DMI target of 200 g of DM/d (including starter and forage). Successful-combination calves’ milk remained stable until calves met a DMI target of 200 g of DM/d; milk was then reduced until weaning at d 70. Groups of calves were alternately assigned to either grass hay or silage-based TMR (\( n = 6 \) groups per treatment).

\(^{2}\)Analysis was performed on square-root-transformed data; raw means and SE are reported.
When the “failed” calves were removed from the wean-by-age treatment, there were no longer differences in final BW at 84 d or ADG during weaning. During weaning, successful-age calves tended to have reduced heart girth growth compared with successful-intake and successful-combination calves \((t_{1,72.0} > 2.0, P < 0.10)\). After weaning, successful-age calves had (or tended to have) greater body barrel growth \((t_{1,71.2} < 2.4, P < 0.02)\), whereas successful-intake and successful-combination calves had greater withers height growth \((t_{1,71.0} < 1.9, P < 0.06)\). We detected no difference in final structural body measures at d 84. Successful-age calves had a higher gain-to-feed ratio compared with successful-intake during and after weaning \((t_{1,71.8} < 2.5, P < 0.01)\) and tended to have a higher gain-to-feed ratio after weaning compared with successful-combination calves \((t_{1,70.8} < 1.9, P < 0.06)\). Compared with successful-intake and successful-combination calves, successful-age calves had higher milk intakes \((t_{1,68.6} > 8.7, P < 0.001)\) and lower starter intake \((t_{1,69.8} > 5.1, P < 0.001)\) during weaning. Postweaning, successful-age calves had lower starter intakes \((t_{1,71.9} > 2.7, P < 0.008)\). Unrewarded visits were lower for successful-age calves during weaning \((t_{1,70.2} > 3.7, P < 0.001)\) but higher after weaning \((t_{1,72.8} > 2.0, P < 0.05)\) compared with successful-intake and successful-combination calves.

Removing “failed” calves from the wean-by-age treatment had no effect on forage treatments, so these results are not presented.

Forage Treatments

**Descriptive Results: Age and Duration of Weaning.** Weaning age and duration were similar in groups assigned to hay versus TMR treatments, with no evidence of an interaction with weaning method. An equal number of calves failed to meet intake targets within the wean-by-intake \((n = 4\) hay; \(n = 4\) TMR) and wean-by-combination treatments \((n = 1\) hay; \(n = 1\) TMR). Within the successful-intake treatments, hay and TMR calves had similar weaning ages \((56.4 \pm 5.6\) d, range: 49–63 d; vs. 56.2 ± 6.1 d, range: 48–70 d, respectively) and weaning durations \((17.0 \pm 4.3\) d, range 12–26 d; vs. 16.6 ± 3.7 d, range: 12–22 d, respectively). Within the successful-combination treatments, hay calves had a longer weaning duration with less individual variability compared with TMR calves \((30.9 \pm 3.3\) d, range: 24–34 d; vs. 25.5 ± 7.1 d, range: 10–34 d, respectively). Milk allowances after the initial...
step-down on d 31 were also similar between forage treatments (hay: 7.5 ± 0.8 L/d; TMR: 7.0 ± 1.0 L/d).

Feed Intake, Unrewarded Visits, and Growth. No differences in milk intake were found between forage treatments (Table 4). Starter and forage intakes increased with age, especially starting after the initial milk reduction at d 31 for both hay and TMR calves (Figure 5). Before weaning, hay calves tended to consume more forage than TMR calves (F[1,8.5] = 4.1, P = 0.08). During weaning, hay and TMR calves consumed similar amounts of forage, but hay calves consumed more starter than TMR calves (F[1,8.5] = 8.8, P = 0.02), resulting in hay calves having greater total DMI during weaning compared with TMR calves (F[1,7.0] = 11.8, P = 0.009). After weaning, hay calves continued to consume more starter than TMR calves (F[1,9.8] = 10.1, P = 0.01), but TMR calves consumed more forage than hay calves (F[1,9.8] = 38.2, P < 0.001). After weaning, hay and TMR calves had similar total DMI. We found no effect of forage treatment on unrewarded visits before or during weaning, but TMR calves tended to show more unrewarded visits after weaning compared with hay calves (F[1,7.0] = 4.8, P = 0.06).

Few differences in BW occurred between forage treatments until wk 7, after which TMR calves showed lower BW for the remainder of the 12-wk period. Hay calves weighed about 5 kg more at d 84 compared with TMR calves (F[1,8.6] = 6.2, P = 0.04). During weaning, hay calves tended to have higher ADG than TMR calves (F[1,9.6] = 4.2, P = 0.06). No differences in feed efficiency or structural growth were found between forage treatments (Table 5).

Table 3. Least squares means (±SE) of growth measurements of Holstein calves in the wean-by-age (n = 31), successful-intake (n = 27), and successful-combination (n = 33) weaning treatments; results are shown separately for each period

| Response variable | Wean-by-age | Successful-intake | Successful-combination | SE | P-value |
|-------------------|-------------|-------------------|------------------------|----|---------|
| Preweaning (d 2–30) |             |                   |                        |    |         |
| Heart girth (HG, cm/d) | 0.44        | 0.49              | 0.46                   | 0.03 | 0.27   |
| Body barrel (BB, cm/d)  | 0.55        | 0.64              | 0.58                   | 0.04 | 0.26   |
| Withers height (WH cm/d) | 0.27a       | 0.29b             | 0.25b                  | 0.02 | 0.09   |
| ADG (kg/d)         | 0.83        | 0.88              | 0.85                   | 0.04 | 0.50   |
| Gain:feed (kg/kg of DM) | 0.82        | 0.89              | 0.83                   | 0.06 | 0.26   |
| Weaning (d 31–69)  |             |                   |                        |    |         |
| HG (cm/d)          | 0.26a       | 0.30b             | 0.31a                  | 0.02 | 0.01   |
| BB (cm/d)          | 0.46b       | 0.54a             | 0.54a                  | 0.03 | 0.03   |
| WH (cm/d)          | 0.21        | 0.20              | 0.21                   | 0.01 | 0.52   |
| ADG (kg/d)         | 0.71b       | 0.85a             | 0.82a                  | 0.04 | 0.63   |
| Gain:feed (kg/kg of DM) | 0.55        | 0.56              | 0.54                   | 0.04 | 0.13   |
| Postweaning (d 70–84) |           |                   |                        |    |         |
| HG (cm/d)          | 0.49        | 0.43              | 0.45                   | 0.05 | 0.38   |
| BB (cm/d)          | 0.86b       | 0.58a             | 0.64a                  | 0.08 | 0.009  |
| WH (cm/d)          | 0.20a       | 0.27b             | 0.25a                  | 0.04 | 0.02   |
| ADG (kg/d)         | 1.52        | 1.43              | 1.51                   | 0.05 | 0.27   |
| Gain:feed (kg/kg of DM) | 0.60a       | 0.49b             | 0.53b,ab               | 0.03 | <0.001 |
| Final growth measures at d 84 |       |                   |                        |    |         |
| Final HG (cm)      | 111.2b      | 113.2a            | 112.8a                 | 1.06 | 0.05   |
| Final BB (cm)      | 129.9b,ab   | 132.9a            | 132.3b,ab              | 1.15 | 0.05   |
| Final WH (cm)      | 97.2b       | 98.6a             | 97.9b                  | 0.52 | 0.07   |
| Final weight (kg)  | 117.7b      | 123.7            | 122.3                  | 3.11 | 0.04   |

*Means with different superscripts within a row indicate a tendency (0.05 < P ≤ 0.1) between wean-by-age, successful-intake, and successful-combination calves.

*Means with different superscripts within a row indicate a significant difference (P ≤ 0.05) between wean-by-age, successful-intake, and successful-combination calves.

All calves received 12 L/d of milk until d 31, when milk was reduced by 25% based on individual average milk intake. Wean-by-age calves’ milk remained stable until d 62, when milk was reduced until weaning at d 70. Successful-intake calves’ milk was further reduced by 25% when calves met DMI targets of 200, 600, and 1,150 g of DM/d (including starter and forage). Successful-combination calves’ milk remained stable until calves met a DMI target of 200 g of DM/d; milk was then reduced until weaning at d 70. Groups of calves were alternately assigned to either grass hay or silage-based TMR (n = 6 groups per treatment).

DISCUSSION

Weaning Treatments

To smoothly transition onto solid feed, calves need to be consuming solid feed before milk removal. Weaning strategy is especially important to consider when feeding larger volumes of milk (Khan et al., 2011b). Using solid feed intake as a criterion ensures that weaning is only started when calves are consuming solid feed (Roth et al., 2009; de Passillé and Rushen, 2012), and thus allows calves to go through weaning at their own pace (Benetton et al., 2019). Our study compared 2 intake-
based weaning methods, one using 3 intake targets and a step-down reduction method (wean-by-intake) and the other using 1 intake target and a linear reduction method (wean-by-combination). Compared with previous studies examining intake-based weaning methods (de Passillé and Rushen, 2012, 2016; Benetton et al., 2019), our treatments were designed to be more gradual and thus to reduce unrewarded visits to the milk feeder and minimize growth checks around weaning.

We removed 17 calves from the analysis, which may have affected our results. Seven of these calves were removed due to sickness, low preweaning milk intakes, and poor growth. The remaining 10 calves failed to meet the final weaning target of 1,150 g of DM/d of solid feed for wean-by-intake treatment (8 out of 35 calves) or the 200 g of DM/d target for wean-by-combination treatment (2 out of 35 calves). As these failed calves did not follow the treatment protocol, we removed them from our statistical test of treatment effects but still provide their results for descriptive purposes. These failed calves weighed numerically about 20 kg less than successful-intake, successful-combination, and wean-by-age calves. Lower growth rates in these failed calves were likely due to low solid feed intakes before 9 wk when calves were force-weaned. Previous work investigating intake-based weaning methods has also found that a portion of calves consume very little solid feed and fail to meet intake targets. For example, de Passillé and Rushen (2012) found that 11 out of 60 calves failed to meet either the 200 g/d or 400 g/d starter intake targets before d 74 of age. Benetton et al. (2019) found that 6 out of 16 calves failed to reach the final starter intake target of 1,300 g/d by 62 d of age; when given until 84 d to wean, 3 out of 46 calves still failed to reach the final target. Both studies reported reductions in starter intake and final BW compared with their successful counterparts.

The use of automated starter and forage feeders that restrict use to a single calf may have influenced the number of failed calves seen in this study, as calves fed this way must find the feeder and feed on their own. Under naturalistic conditions, dairy cattle graze together, and calves rely on older animals to learn where and what feed to consume (reviewed by Whalin et al., 2021). Calves that consume very little solid feed before weaning may be less exploratory and may struggle to find and learn how to use the automated feeders, as reported by Neave et al. (2018, 2019). In addition, because the feeders we used restricted entry to one calf at a time, calves may have experienced competitive interactions at the feeder; low-intake calves may be less dominant and thus struggle to access the feeders or may be more often displaced. Additionally,
high milk allowances can increase the risk that some calves consume little solid feed before weaning (Khan et al., 2016), but low solid feed intakes can be an issue even when calves are fed less milk. For example, Roth et al. (2009) reported weaning ages between 45 and 98 d in calves fed 6 L/d of milk and weaned based on starter intake (using an initial target of 0.7 kg/d and a final target of 2 kg/d). Neave et al. (2018) also found large variability in age (6–29 d) to first consume 40 g/d of starter and variation in starter DMI over 7 to 98 d (0.33–1.24 kg/d) in calves fed 6 L/d of milk. An advantage of weaning methods based on intake is that these programs help identify calves that consume little solid feed before weaning; these calves might not be

![Graph showing total weight gain of calves from 2 to 84 d of age in relation to total starter intake over the same period.](image)

**Figure 4.** Total weight gain of calves (n = 101) from 2 to 84 d of age increased linearly in relation to total starter intake over the same period (slope = 0.38 ± 0.03).

| Response variable     | Hay (kg/d) | TMR (kg/d) | SE  | P-value |
|-----------------------|------------|------------|-----|---------|
| Preweaning (d 2–30)   |            |            |     |         |
| Milk intake (L/d)     | 8.8        | 8.4        | 0.21| 0.24    |
| Starter DMI (kg/d)    | 0.025      | 0.026      | 0.005| 0.93   |
| Forage DMI (kg/d)     | 0.007      | 0.004      | 0.001| 0.08   |
| Total DMI (kg/d)      | 1.05       | 1.00       | 0.03| 0.29   |
| Unrewarded visits (no./d) | 1.5      | 1.3        | 0.28| 0.85   |
| Weaning (d 31–69)     |            |            |     |         |
| Milk intake (L/d)     | 4.3        | 4.3        | 0.15| 0.84    |
| Starter DMI (kg/d)    | 0.96       | 0.75       | 0.07| 0.03    |
| Forage DMI (kg/d)     | 0.10       | 0.11       | 0.01| 0.65    |
| Total DMI (kg/d)      | 1.54       | 1.33       | 0.05| 0.009   |
| Unrewarded visits (no./d) | 9.4      | 8.8        | 0.63| 0.40    |
| Postweaning (d 70–84) |            |            |     |         |
| Starter DMI (kg/d)    | 2.88       | 2.50       | 0.10| 0.01    |
| Forage DMI (kg/d)     | 0.15       | 0.33       | 0.02| <0.001  |
| Total DMI (kg/d)      | 3.00       | 2.82       | 0.10| 0.19    |
| Unrewarded visits (no./d) | 2.7      | 3.4        | 0.27| 0.06    |

1All calves received 12 L/d of milk until d 31, when milk was reduced by 25% based on individual average milk intake. Calves were weaned either by age (milk remained stable until d 62, when milk was reduced until weaning at d 70), by successful intake (milk was further reduced by 25% when calves met DMI targets of 200, 600, and 1,150 g of DM/d, including starter and forage), or by successful combination (milk remained stable until calves met a DMI target of 200 g of DM/d; milk was then reduced until weaning at d 70). Groups of calves were alternately assigned to 1 of 2 forage treatments: grass hay or silage-based TMR (n = 6 groups per treatment).

2Analysis was performed on square-root-transformed data; raw means and SE are reported.

Table 4. Least squares means (±SE) of daily milk intake, starter DMI, forage DMI, total DMI, and number of unrewarded visits to the milk feeder of groups of Holstein calves receiving hay (n = 6 groups) and TMR (n = 6 groups); results are shown separately for each period.
Figure 5. Arithmetic means (±SE) for descriptive purposes of (A) starter intake, (B) forage intake, and (C) BW for Holstein calves aged 1 to 12 wk. Values are shown separately for groups of calves receiving grass hay (n = 6 groups) or silage-based TMR (n = 6 groups). All calves received 12 L/d of milk until d 31, when milk was reduced by 25% based on individual average milk intake. Calves were weaned either by age (milk remained stable until d 62, when milk was reduced until weaning at d 70), by successful intake (milk was further reduced by 25% when calves met DMI targets of 200, 600, and 1,150 g of DM/d, including starter and forage), or by successful combination (milk remained stable until calves met a DMI target of 200 g of DM/d; milk was then reduced until weaning at d 70). Groups of calves were alternately assigned to forage treatment.
identified on farms that wean by age. One implication of our results is that monitoring for low intake would be beneficial regardless of weaning method, but new research will be required to determine how best to manage these low-intake calves.

The 2 intake-based weaning methods (successful-intake and successful-combination) resulted in similar BW and structural body measures at 84 d, whereas wean-by-age calves had reduced BW, body barrel, heart girth, and withers height at 84 d. This lower BW seen in wean-by-age calves was likely driven by low starter intake during the weaning period (0.7 kg of DM/d less starter than successful-intake and 0.4 kg of DM/d less than successful-combination calves). At wk 9, before the final milk reduction, wean-by-age calves were only consuming approximately 0.64 kg of DM/d (~0.72 kg/d). Although this aligns with the recommended starter intake level for weaning calves (~0.68 kg/d of starter; USDA, 2016), it is far less than the 2 kg of DM/d and 1.3 kg of DM/d of starter intake consumed by successful-intake and successful-combination calves at wk 9, respectively. When calves with low solid feed intake were removed from the wean-by-age treatment in the post-hoc analysis, differences in growth were no longer present between successful-age calves and successful-intake and successful-combination calves.

This finding is consistent with the strong relationship between growth and starter intake illustrated in our regression analysis of total weight gain and accumulated starter intake from d 2 to 84. Reduced starter intake before weaning delays rumen development and reduces rumen capacity, leaving the calf unprepared for solid feed consumption, digestion, and growth after weaning. Reduced rumen capacity and development is also likely why wean-by-age calves were unable to consume similar amounts of solid feed after weaning compared with successful-intake and successful-combination calves. Wean-by-age calves would likely have benefited from a longer weaning duration than the 1-wk milk reduction implemented at 62 d. Reduced starter intake before weaning delays rumen development and reduces rumen capacity, leaving the calf unprepared for solid feed consumption, digestion, and growth after weaning. Reduced rumen capacity and development is also likely why wean-by-age calves were unable to consume similar amounts of solid feed after weaning compared with successful-intake and successful-combination calves.

Table 5. Least squares means (±SE) of growth measurements of groups of Holstein calves receiving hay (n = 6 groups) and TMR (n = 6 groups); results are shown separately for each period1

| Response variable | Hay   | TMR   | SE    | P-value |
|-------------------|-------|-------|-------|---------|
| Preweaning (d 2–30) |       |       |       |         |
| Heart girth (HG, cm/d) | 0.45  | 0.47  | 0.03  | 0.63    |
| Body barrel (BB, cm/d) | 0.57  | 0.62  | 0.04  | 0.29    |
| Withers height (WH, cm/d) | 0.28  | 0.27  | 0.02  | 0.66    |
| ADG (kg/d)            | 0.88  | 0.82  | 0.04  | 0.27    |
| Gain:feed (kg/kg of DM) | 0.86  | 0.83  | 0.04  | 0.55    |
| Weaning (d 31–69) |       |       |       |         |
| HG (cm/d)            | 0.31  | 0.27  | 0.01  | 0.04    |
| BB (cm/d)            | 0.52  | 0.50  | 0.03  | 0.68    |
| WH (cm/d)            | 0.21  | 0.20  | 0.01  | 0.29    |
| ADG (kg/d)            | 0.85  | 0.74  | 0.04  | 0.86    |
| Gain:feed (kg/kg of DM) | 0.54  | 0.53  | 0.02  | 0.76    |
| Postweaning (d 70–84) |       |       |       |         |
| HG (cm/d)            | 0.44  | 0.47  | 0.03  | 0.40    |
| BB (cm/d)            | 0.63  | 0.75  | 0.07  | 0.18    |
| WH (cm/d)            | 0.23  | 0.25  | 0.02  | 0.33    |
| ADG (kg/d)            | 1.46  | 1.51  | 0.05  | 0.44    |
| Gain:feed (kg/kg of DM) | 0.50  | 0.57  | 0.03  | 0.12    |
| Final growth measures at d 84 |       |       |       |         |
| Final HG (cm)         | 112.6 | 112.1 | 0.80  | 0.58    |
| Final BB (cm)         | 131.7 | 131.7 | 1.10  | 0.96    |
| Final WH (cm)         | 97.6  | 98.2  | 0.49  | 0.41    |
| Final weight (kg)     | 123.5 | 119.2 | 1.56  | 0.04    |

1All calves received 12 L/d of milk until d 31, when milk was reduced by 25% based on individual average milk intake. Calves were weaned either by age (milk remained stable until d 62, when milk was reduced until weaning at d 70), by successful intake (milk was further reduced by 25% when calves met DMI targets of 200, 600, and 1,150 g of DM/d, including starter and forage), or by successful combination (milk remained stable until calves met a DMI target of 200 g of DM/d; milk was then reduced until weaning at d 70). Groups of calves were alternately assigned to 1 of 2 forage treatments: grass hay or silage-based TMR (n = 6 groups per treatment).
milk allocated and amount consumed has been reported in calves fed by automated feeders (Nielsen et al., 2008; Sweeney et al., 2010; Benetton et al., 2019), and even calves fed restricted milk allowances (6 L/d) do not always consume their full allotment (Rosenberger et al., 2017). Differences between milk allowance versus milk consumed may relate to how automated feeders allocate milk throughout the day and how individual calves interact with the feeder. For calves to receive milk from the automated feeders, the minimum milk allocation must have accrued. We set the minimum milk allocation to 0.5 L so that calves were able to ingest small portions of milk over several meals, but this type of meal pattern can increase milk feeder occupancy and competition (Senn et al., 2000; Jensen, 2004; Jensen, 2009), potentially reducing intake. Also, the final milk allowance was allocated at 2000 h, perhaps preventing some calves from receiving milk at night.

Contrary to our expectations, both intake-based weaning methods resulted in high numbers of unrewarded visits, despite introducing a gradual removal of milk after each intake target. Benetton et al. (2019) and de Passillé and Rushen (2016) also found a high number of unrewarded visits in calves weaned based on intake. Unrewarded visits to the milk feeder are considered a sign of hunger, with restricted-fed calves having more frequent unrewarded visits than those provided higher milk allowances (Jensen, 2006; De Paula Vieira et al., 2008), which would imply that calves weaned based on a solid feed intake experienced more hunger during weaning compared with calves weaned by age. Indeed, hunger could have driven calves to reach the intake targets quickly, resulting in further reductions in milk allowance. However, this result warrants further investigation, as it appears contradictory that the wean-by-intake and wean-by-combination calves, who had higher ADG and feed consumption, were more hungry than wean-by-age calves who showed poorer growth and intakes. It is possible that factors other than hunger, such as frustration, may have influenced the number of unrewarded visits at the milk feeder. Frustration occurs when an individual is kept from attaining a goal at the time they expect to receive it (Berkowitz, 1989). Previous work has suggested that animals experience frustration when an expected reward is not delivered (Amsel, 1958; Carlstand, 1986). During weaning, automated milk feeders reduce the amount of milk and the times at which milk is available, potentially creating a frustrating situation for the calf. Given that calves have consistent feeding times (Jensen, 2004), the inconsistency and uncertainty of when and how much milk calves will have available may lead to further attempts to access milk. This could also explain the low frequency of unrewarded visits seen in wean-by-age calves at 5 to 9 wk when milk allowance remained consistent, and the high frequency of unrewarded visits at 10 wk when milk allowance was reduced for these calves. We encourage future work to develop and test predictions distinguishing feelings of hunger and frustration around weaning.

Forage Treatments

Over the past 2 decades there has been a renewed interest in providing milk-fed calves access to forage (Coverdale et al., 2004; Castells et al., 2012, 2013; Pazoki et al., 2017). However, only a few studies have provided calves with fermented silages (Castells et al., 2012; Mirzaei et al., 2017). Because calves typically transition onto a fermented ration later in life, our second objective was to compare feed intake, behavior, and growth of calves fed either grass hay or a lactating cow TMR and how these forage types influence the weaning transition. During weaning, hay calves had greater total DMI and ADG compared with TMR calves, resulting in a greater final BW at 84 d. The increased DMI was driven by hay calves consuming more starter during weaning compared with TMR calves. The TMR calves were likely unable to achieve the same total DMI as hay calves due to the high moisture of the TMR. Overvest et al. (2016) also found that calves fed a silage-based TMR, similar to the one fed in our study, had reduced DMI and final BW compared with calves fed starter and hay separately. Interestingly, they found similar feed intake across all treatments on an as-fed basis and similar gain-to-feed ratios after weaning, suggesting that the digestibility of the TMR was not the cause of reduced growth but rather that the calves fed TMR were unable to achieve equivalent DMI. Khan et al. (2020) found that calves fed a forage-based starter (fermented alfalfa), with a similar moisture content (45% DM) to our TMR, had lower solid feed DMI during the milk-feeding period and reduced growth during and after weaning. The high moisture of the TMR also helps explain why TMR calves during weaning had reduced starter DMI but similar forage DMI and milk intakes compared with hay calves. Young calves have a smaller rumen capacity to accommodate forage bulk before and during weaning, so consumption of forage with high moisture may increase gut fill to the extent that DMI and nutrient supply are reduced (Khan et al., 2016). The reduced starter intake during weaning likely left TMR calves hungry, especially around complete milk removal. This may explain why TMR calves tended to have more unrewarded visits at the milk feeder after weaning compared with hay calves. Overall, the increase in total DMI and ADG during weaning, combined with the reduced number of unrewarded visits after weaning,
suggest that hay calves experienced a smoother transition to a solid feed diet.

After weaning, TMR calves consumed less starter compared with hay calves but had similar ADG, likely due to their higher forage intake after weaning. The TMR had a greater level of energy and protein than the hay due to the inclusion of concentrate primarily comprised of soybean meal and corn meal, potentially making the TMR more palatable. Miller-Cushon et al. (2014) demonstrated that calves exhibit clear preference for certain high-energy and high-protein feed types, including soybean meal and corn meal. Because the TMR had both forage and concentrate, TMR calves were likely getting a portion of their grain source from the TMR, explaining the lower starter intake of TMR calves during and after weaning. This effect would be more pronounced after weaning, when milk was no longer available and calves were required to select their diet from starter and forage. In addition, forage particle length and bulk can affect feed intake; shorter particle lengths and higher-density feeds result in greater digestibility, higher intakes, and reduced rumen fill (Coon et al., 2018; Omidi-Mirzaei et al., 2018). The shorter particle length in the TMR compared with the hay may have promoted greater intake of the TMR. The fermentation of the TMR likely improved digestibility, as microbes had already begun breaking down the TMR, making nutrients more accessible to the calf. Another explanation for the increase in forage intake in TMR calves could be changes in the rumen. The fermented feeds in the TMR may have created a more favorable environment for butyrate production (Esdale et al., 1968), allowing for more rapid rumen development and a greater capacity for forage intake. Overall, it is unclear why TMR calves had greater intake of forage after weaning. Improved understanding of how fermented forages affect rumen development, as well as preferences for different forage types, may shed more light on this finding.

One strength of the current study is that the weaning treatments were tested within group, and multiple groups were assessed providing some basis to generalize our conclusions. However, some aspects of the study, including the size and layout of the pens used, as well as the specifics of the milk and grain feeders, likely affected study results. Future studies should attempt to assess the effects of weaning treatments across multiple farms. The current study population reflects healthy calves that completed weaning treatment protocols, but 10 of 70 calves did not meet the targets required for the wean-by-intake and wean-by-combination treatments; more work is required to understand why some calves are slow to start their intake of solid feed. A weakness of the current study is that moisture content of orts was not taken into consideration when calculating the DM of forage, potentially resulting in an underestimation of forage DMI. In addition, the effect of the forage treatments was tested only at the group level, providing a less powerful test of this treatment. Future work should use more groups or apply more sensitive within-group testing methods for this effect.

CONCLUSIONS

Calves weaned using an intake criterion showed greater solid feed intake, postweaning weights, and structural growth compared with calves weaned at a fixed age. These results illustrate that weaning based on intake is a promising strategy to manage weaning at the individual level and ensure that calves are consuming solid feed before weaning; however, unrewarded visits to the milk feeder were more frequent in calves weaned based on intake, potentially indicating hunger or frustration during weaning. Some calves (regardless of treatment) consume little solid feed before weaning; weaning methods based upon intake can help identify these animals, but how they should be managed is not clear. Forage type can influence the transition onto solid feed. Offering grass hay to milk-fed calves can improve solid feed intake and ADG during weaning, resulting in greater BW and fewer signs of hunger postweaning compared with calves fed a lactating cow TMR.

ACKNOWLEDGMENTS

We thank the staff and students of the University of British Columbia (UBC) Animal Welfare Program working at the UBC Dairy Education and Research Centre (Agassiz, BC, Canada), especially Elizabeth Russell, Bianca Vandresen, Amandine Mauger, and Rodrigo Held Montaldo, for help with the data collection. We also thank Joao Costa (University of Kentucky, Lexington, KY) for discussions on study design and interpretation of results. General funding for the UBC Animal Welfare Program (Vancouver, BC, Canada) is provided by the Natural Sciences and Engineering Research Council of Canada (NSERC; Ottawa, ON, Canada) Industrial Research Chair, with contributions from Dairy Farmers of Canada (Ottawa, ON, Canada), Alberta Milk (Edmonton, AB, Canada), Saputo (Montreal, QC, Canada), British Columbia Dairy Association (Burnaby, BC, Canada), Merek (Kirkland, QC, Canada), British Columbia Cattle Industry Development Fund (Kamloops, BC, Canada), Boehringer Ingelheim (Burlington, ON, Canada), Semex Alliance (Guelph, ON, Canada), Lactanet (Sainte-Anne-de-Bellevue, QC, Canada), Dairy Farmers of Manitoba (Winnipeg, MB, Canada), and SaskMilk (Regina, SK, Canada).
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