ABSTRACT

The aim of this systematic review was to summarize the literature assessing the effects of weaning practices on performance, behavior, and health of dairy calves. Only published, peer-reviewed articles written in English and specifically assessing the effects of weaning treatments on dairy calves were eligible for inclusion. Studies had to include 2 or more treatment groups that addressed at least one of 4 interventions: weaning age (i.e., when milk was fully removed), weaning duration (i.e., number of days from start of milk reduction to when milk was fully removed), weaning criteria (e.g., age vs. intake), or alternative weaning methods (e.g., water dilution). Outcome measures could include starter intake, growth (body weight or average daily gain), behaviors (5 specific sucking behaviors; play behavior; lying behavior; vocalizations; unrewarded visits to an automated milk feeder), and health (mortality rate, diarrhea, and respiratory illness). We conducted 3 targeted searches using Web of Science and PubMed. The articles underwent a 2-step screening process, resulting in a final sample of 44 studies. The majority of studies investigated weaning age (n = 22), followed by weaning duration (n = 13), weaning criteria (n = 9), and other weaning methods such as dilution, linear vs. step-down milk reduction, or meal-based approaches (n = 6). There was consensus for positive effects (or at least no negative effects) on overall growth of calves weaned at later ages, over longer durations, based on starter intake, or weaned using step-down or meal-based milk removal approaches. This is despite reduced starter intake in calves weaned at later ages; most studies found improved starter intake in calves weaned over longer durations. Weaning based on starter intake had superior growth and feed intakes compared with calves weaned at a fixed earlier age. Few studies assessed interactive effects of weaning method and milk allowance. However, weaning after 8 wk appears to support superior weight gain, provided pre-weaning milk allowances are adequate (above 6 L/d). Weaning can lead to hunger-related behaviors and reduced welfare, yet only half of the studies assessed the effects of weaning method on calf behavior. Weaning at later ages can reduce signs of hunger (based on unrewarded visits to the milk feeder), but it is unclear if weaning over longer durations or weaning by starter intake reduces or prolongs hunger. There was little consensus among the few studies that measured oral behaviors of calves. Positive welfare indicators, such as play behavior, were rarely measured, yet are crucial to understanding the emotional states of calves during this potentially stressful diet transition. Health was rarely the primary objective of the study, with low sample sizes to conduct statistical comparisons. Overall, there remains significant knowledge gaps in our understanding of how best to wean calves. A successful weaning program must minimize signs of hunger while promoting high growth and feed intakes, so we encourage future work to include behavioral indicators of hunger and positive welfare to evaluate how weaning methods are experienced by the calf.

Key words: gradual weaning, milk reduction, development, morbidity

INTRODUCTION

Weaning is a crucial challenge experienced by the dairy calf in the first few months of life as it transitions from a pseudo-monogastric to a functioning ruminant. Under semi-natural conditions when a calf is reared by the dam, weaning occurs over several months and is often not completed until the calf is 8 to 11 mo of age (reviewed by Whalin et al., 2021). This is starkly different from traditional weaning practices on dairy farms where calves are weaned 5 to 6 mo earlier and over shorter periods of time, often less than a week (reviewed by Khan et al., 2016). Weaning is commonly
described as stressful (Weary et al., 2008) and is often accompanied by signs of hunger and weight loss (de Passillé et al., 2011b; Dennis et al., 2018). Over the past 2 decades researchers have debated which weaning strategies are best at promoting rumen development and growth while minimizing signs of hunger and distress. These weaning strategies have largely focused on weaning ages (Eckert et al., 2015; de Passillé and Rushen, 2016; Schwarzkopf et al., 2019) and weaning durations (Sweeney et al., 2010; Hill et al., 2012) but with little consensus.

There is a large variation in weaning practices on dairy farms. In the United Kingdom, 32% of farmers weaned calves by 8 wk of age (Mahendran et al., 2022) with similar mean weaning ages reported in the Czech Republic (9 wk; Staněk et al., 2014), Canada (8 wk; Medrano-Galarza et al., 2017), and the United States (9 wk; USDA, 2014). Other studies report that a large proportion of farmers wean calves at later ages. In the United States, 31% of farmers reported weaning calves at ≥10 wk (USDA, 2014), while in United Kingdom (Mahendran et al., 2022) and Austria (Klein-Jöbstl et al. 2015), 33 and 46% of farmers reported weaning calves at ≥12 wk, respectively. However, some farmers still wean calves at <6 wk [e.g., 7.5% of farmers in the United States (USDA, 2014); 2.8% of farmers in the United Kingdom (Mahendran et al., 2022)]. How farmers decide when to wean calves also appears to differ. For example, in the United Kingdom, 33% of farmers weaned based on starter intake, 26% by age, and 21% by weight (Mahendran et al., 2022) while in the Czech Republic, 62% of farmers weaned by age, 20% by starter intake, and 18% based on housing capacity (Staněk et al., 2014). However, several studies reported that farmers often use a combination of methods to assess if a calf is ready to wean (USDA, 2014; Mahendran et al., 2022; Sinnott et al., 2023). The way in which milk is removed is not often systematically reported, but 2 surveys reported dilution of milk was a weaning method used by 32% of Swedish farmers (Pettersson et al., 2001) and 25% of Canadian farmers using manual milk feeding methods (Medrano-Galarza et al., 2017). These variable weaning methods reflect some uncertainty by both farmers and veterinarians around which weaning methods are best to utilize (Palczynski et al., 2020), so decisions of when and how to wean often came down to “ease” of the task, time constraints, or personal experience (Russell et al., 2022; Palczynski et al., 2020). Farmers described key indicators of a successful weaning program to include high solid feed intake, play behavior, few vocalizations, high growth, and low mortality rate (Russell et al., 2022). Taken together, there is a lack of clarity on best weaning practices and a need for consensus on which weaning methods best promote growth and health while minimizing hunger and distress.

The aim of this systematic review was to provide an overview of and identify knowledge gaps in the scientific literature on the effects of weaning practices (weaning age, duration, and criteria) on behavior (including sucking behavior, activity, and behavioral signs of hunger), performance (including starter intake and growth), and health (including diarrhea, respiratory illness, and mortality) of dairy calves. It was predicted that weaning methods that remove milk at later ages, over longer periods, or based on starter intake (rather than based on age, weight or using milk dilution), will reduce signs of hunger and abnormal sucking behavior, and will promote feed intake and growth. In addition, later weaning ages, longer weaning durations, and weaning based on starter intake were predicted to reduce mortality rate and incidence of diarrhea and respiratory illness, due to reduced stress at weaning.

MATERIALS AND METHODS

Protocol and Registration

This review is a sister study to Welk et al. (2023) which investigated the effects of milk feeding practices on performance, behavior, and health. A review protocol was created a priori in accordance with PRISMA-P guideline (Moher et al., 2015). The protocol can be found in Supplemental File S1 (https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023).

Eligibility Criteria

Primary Study Design, Characteristics, and Population. Only peer-reviewed studies that presented primary research with either an experimental or observational study design were included in this review. In addition, only studies in English were included and full text needed to be available online or through Aarhus University library. The population of study could include dairy calves with no restrictions on sex, breed, or production type. Studies were excluded if milk allowance was <4 L/d (<3 L/d for Jersey) in the first 21 d of life, or if cow-calf rearing systems were utilized. Finally, studies assessing weaning treatments had to manage calves similarly during the pre-weaning period (before weaning treatments commenced). Thus, milk allowance during the pre-weaning period had to be the same between weaning treatments (unless an appropriate experimental design was done such as 2 × 2 factorial study design).

Intervention Groups. Studies had to include 2 or more treatment groups that addressed one or more of...
the following 4 interventions: weaning age, weaning duration, weaning criteria, and alternative weaning methods. Weaning age was defined as the age when milk was fully removed. Weaning duration was defined as the number of days from when milk reduction started until milk was fully removed; weaning age had to be the same between treatments in studies investigating different weaning durations. Weaning criteria was defined as the criteria used to decide when to wean a calf (e.g., age, starter intake, weight). Alternative weaning methods were defined as weaning methods that did not fall under the above 3 interventions (e.g., weaning by water dilution), and to be eligible, weaning treatments had to have the same weaning age, weaning duration, and weaning criteria. Studies could also include 2 or more treatment groups that addressed one or more of the following 3 topics on milk feeding practices: milk allowance, milk feeding frequency, and milk feeding method. A description of milk feeding practices are presented in Welk et al. (2023).

**Outcome Measures.** One or more outcome measures related to behavior, feed intake and growth, or health had to be included in the studies. For behavior, 5 specific sucking behaviors were defined: nutritive sucking on teat (sucking on milk teat and ingesting milk), non-nutritive sucking on teat (sucking on milk teat, or a dry teat, and no milk is ingested), non-nutritive sucking on pen fixtures (sucking on pen fixtures including bars, rim of bucket, etc.), other oral behaviors (biting, licking, nibbling pen fixtures, or holding objects in the mouth), and cross-sucking (sucking on any body part of another calf). In addition, 2 measures of activity and 2 measures of hunger were included: locomotor play behavior, lying behavior, vocalizations, and, for studies using automated milk feeders, unrewarded visits at the milk feeder (when a calf visits the milk feeder but is not entitled to receive milk). For feed intake and growth studies, outcome measures could include starter intake, BW, or ADG. For studies related to health, outcome measures could include mortality rate, diarrhea, and respiratory illness.

**Literature Search**

Literature searches were conducted in the database of Web of Science and PubMed on March 30, 2022, and August 23, 2022, with no restrictions on the date of publication. An additional search on weaning intervention search terms was conducted on September 15, 2023. Weaning intervention search terms were as follows: wean* or step-down (title) and age or duration or milk reduction or step-down or individual or method* or type* or gradual or abrupt or conventional (topic). Search terms regarding population, milk feeding intervention, and outcome measures were the same as reported in Welk et al. (2023). Search results were uploaded to EndNoteX7 (Clarivate Analytics, Philadelphia, PA). Twelve relevant studies were pre-selected by M. B. Jensen and search results were checked to ensure these studies were included.

**Screening Process**

Studies were exported from EndNoteX7 into Covidence (Veritas Health Innovation, Melbourne, Australia). Duplicate results were documented and removed, and the remaining studies were subjected to 2 rounds of screening. The first round of screening was conducted independently by A. Welk. Titles and abstracts were assessed for relevance using the following questions:

1. Does the title or abstract describe a study involving dairy calves?
2. Does the title or abstract describe an experimental or observational study design?
3. Does the title or abstract include intervention groups on one of the following topics: milk allowance, milk feeding frequency, milk feeding method, weaning age, weaning duration, weaning criteria, or weaning method?

Studies were excluded if one or more of these criteria were not fulfilled. During the second round of screening, full text scans were completed on the remaining studies independently by A. Welk using the following questions:

1. Does the study examine one or more outcome measures: behavior (nutritive sucking on teat, non-nutritive sucking on teat, non-nutritive sucking on pen fixtures, other oral behaviors, cross-sucking, lying time, locomotor play behavior, vocalizations, unrewarded visits at the milk feeder), feed intake and growth (starter intake, starter meal duration, BW, ADG), and health (mortality rate, diarrhea, respiratory disease)?
2. Is the milk allowance during the first 21 d of age of life ≥4 L/d?
3. Is milk allowance reported in L/d? If not, is all relevant information provided to convert milk allowance to L/d?

Records that passed the 2 rounds of screening were used for data collection. The first round of screening was pilot tested independently by A. Welk, M. B. Jensen, and one other researcher on the first 100 studies identified by the initial search in Web of Science. The second round of screening was pilot tested indepen-
Data Extraction

Data from studies meeting the study selection criteria were independently extracted by A. Welk. A standardized form in Covidence was used to extract study-level data and population characteristics. Study-level data included publication year, country, study design, and study period (season). Population characteristics included sample size, breed, production type, length of experimental period, housing type, manual or automated milk feeding, milk allowance, milk type, milk feeding frequency, milk feeding method, starter and forage type, weaning age, weaning duration, weaning criteria, and weaning method. Using a standardized spreadsheet within Excel, detailed descriptions of treatments, outcome measures, methodology, and conclusions were extracted from each paper. Results were tabulated for weaning and post-weaning or overall experimental periods, based on original author’s classification in each study. In general, the weaning period was considered from when milk allowance was initially reduced until when milk was fully removed. Post-weaning period was considered from when milk was fully removed. Results from the pre-weaning period were not reported, as our inclusion criteria required calves to be treated the same before weaning (i.e., the same milk allowance, housing etc.), so no treatment effects occurred before weaning. When authors did not classify milk feeding periods, results were provided over the experimental period. Conclusions were based on reported statistics with significance declared at \( P \leq 0.05 \). We present conclusions as described by the original authors and the reporting direction of the statistically significant effect with “+” indicating the effect was interpreted as positive or desirable, “−” as no effect or neutral effect, “−−” as a negative or undesirable effect, and “+/−” as a mixed or unclear effect.

RESULTS AND DISCUSSION

Search Results

The initial 2 searches in March 2022 and August 2022 generated 1106 studies, 41 of which met our inclusion criteria for weaning practices. For results of the search strategy and study selection, refer to the sister study (Welk et al., 2023) that investigated the effects of milk feeding practices on behavior, health, and performance. Out of the 41 studies, 28 studies solely investigated weaning practices while 13 studies investigated both weaning and milk feeding practices and were thus included in both reviews. The final search in September 2023 generated 94 additional studies. During round one of screening 73 studies were classified as irrelevant while during round 2 of screening 14 studies were excluded due to wrong interventions and 4 studies were excluded due to wrong outcome. Thus, 3 additional studies met our inclusion criteria and a total of 44 studies were included in the systematic review (see Figure 1 for an overview of key findings and knowledge gaps).

The final studies included in this review were published between 1990 and 2023. The studies originated from 5 continents and 13 countries, most commonly North America (n = 22: Canada = 16; United Stated = 6) and Europe (n = 16: Denmark = 3, United Kingdom = 3, Ireland = 2, Netherlands = 3, Switzerland = 2, Germany = 1, Italy = 1, Norway = 1). Additionally, 4 studies originated from Asia (Iran = 4), 1 study from Oceania (New Zealand = 1), and 1 study from South America (Brazil = 1).

Weaning Age

The majority of studies within this review focused on weaning age (n = 22) representing 51% of studies within this review. Of the 22 studies that investigated weaning age, 16 studies measured feed intake and growth, 6 studies measured behavior, and 5 studies measured health. Most studies (n = 17) experimentally compared ‘earlier’ vs. ‘later’ weaning ages. The range of ‘earlier’ ages included 28 d (n = 1), 36 to 42 d (n = 4), 41 to 49 d (n = 7), 50 to 56 d (n = 4), and 57 to 63 d (n = 1); while the range of ‘later’ weaning ages included 49 d (n = 1), 50 to 56 d (n = 2), 57 to 63 d (n = 2), 71 to 84 d (n = 5), 85 to 91 d (n = 5), 92 to 98 d (n = 1), and 119 d (n = 1). The remaining 5 studies consisted of 3 cross-sectional studies and 2 cohort studies with varying weaning ages across farms. The age at which weaning was initiated was not specifically compared in any study.

Feed Intake and Growth.

Thirteen and 16 studies assessed the effects of weaning age on starter intake and growth, respectively (see Table 1 for summary of effect). Of the studies assessing starter intake, the majority (n = 10 studies) reported starter intake over the experimental period, with 6 studies finding a negative effect, 1 study finding a positive effect, and 3 studies reporting no effect of later weaning ages on overall starter intake. Lower starter intakes in calves weaned at later ages is unsurprising since calves weaned at a younger age must find an alternative food source earlier in age (and thus have a longer period consuming only solid feed, compared with calves weaned later). However, 2 studies that reported starter intake specifically during...
the weaning and post-weaning periods found a positive effect of later weaning ages on starter intake. Although age is a confounder, these 2 studies indicate that older calves can consume larger amounts of solid feed during weaning and 2 weeks post-weaning. This may be because older calves are better prepared for milk removal, showing markers of ruminal and gastrointestinal preparation for weaning (Eckert et al., 2015) and allowing for a smoother transition to solid feed.

Figure 1. Overview of key findings and knowledge gaps identified in the 44 studies included in this systematic review. Red boxes represent mediating factors in the pre-weaning or weaning phase that are expected to influence the effects of the weaning methods. Currently, there is little understanding of how these mediating factors influence the effects of the weaning method. Purple boxes represent the 6 main outcomes evaluated. Effects on outcomes are presented for older weaning ages compared with younger weaning ages, longer weaning durations compared with shorter weaning durations, and intake-based weaning compared with age-based weaning. Effect direction: “+” indicates that the effect was interpreted as positive or desirable, “−” as negative or undesirable, “=” as no effect, and “−/+” as mixed or unclear. A minimum of 3 studies for an outcome was required to include a judgment of effect. If ≤2 studies measured an outcome, then the effect was considered unknown (i.e., “?”).
Although the majority of studies reported a negative effect of later weaning ages on starter intake, few studies reported a negative effect on growth. In fact, of the 11 studies that reported ADG over the experimental period, 7 studies found a positive effect of later weaning age while 3 studies found no effect. Of the 13 studies reporting BW over the experimental period, 6 studies found a positive effect of later weaning age while 6 studies found no effect. In addition, 1 study reporting ADG and final BW during the weaning and post-weaning period relative to weaning age found a positive effect of later weaning ages on ADG during weaning and post-weaning. Only 1 study found a negative effect of later weaning ages on ADG during the weaning period. One potential bias of some of the results from these 13 studies is that 5 studies reported final BW within one week after calves on the later weaning age treatments completed weaning, while 2 of these studies reported final BW on the day of weaning. This approach may be misleading, given that growth checks are often seen in the week after weaning. In addition, 1 study reported final BW relative to weaning, so age is a confounding factor. Overall, the evidence points to improved growth in calves that are weaned at later ages, even if starter intake is delayed and/or overall intakes reduced; this growth advantage in later-weaned calves is likely related to the longer periods on milk that supported accelerated growth and reduced behavioral indicators of stress at weaning (see below).

**Behavior.** Only a few studies (n = 6) assessed the effect of weaning age on behavior (see Table 2 for summary of effects). Earlier weaning ages are predicted to increase risk of abnormal sucking or oral behaviors, due to hunger related to early removal of milk and sucking opportunity; however, 3 studies assessing sucking behavior (cross-sucking and non-nutritive sucking/other oral behavior on pen fixtures) found no effect of weaning age. These studies assessed both small (6 vs. 8 wk) and large differences (7 vs. 13 wk) in weaning ages, with a range of observation times (3, 9, or 24 h/wk of behavioral recording), but additional work to complement these 3 studies is needed to determine a conclusive relationship between oral behaviors and weaning age.

Two studies assessed the effect of weaning age on locomotor play, which had contrasting results. Krachun et al. (2010) found that calves weaned earlier (at 7 wk) showed reduced locomotor play around weaning compared with un-weaned calves; however, this effect was not seen in calves weaned later (at 13 wk). Eckert et al. (2015) found no difference in play between calves weaned at 6 wk and 8 wk of age. Earlier weaning ages are predicted to be more stressful and thus reduce locomotory play, a potential positive welfare indicator (Boissy et al., 2007; Ahloy-Dullaire et al., 2018). These mixed findings could be due to the difference in weaning age between study treatments (difference of 6 vs. 2 wk, respectively), difference in housing conditions that are likely to affect play (group vs. individual, respectively), or differences in how play behavior was observed (32 h/wk continuously vs. 3 h/wk instantaneously, respectively). Play behavior occurs sporadically and only takes up a small proportion of a calf’s active time (Jensen et al., 2015) so it is recommended to observe calves for 24 h periods or for their entire active time to accurately measure play behavior (Sutherland et al. 2014; Jensen et al., 2015; Miguel-Pacheco et al. 2015). Krachun et al. (2010) also noted that age could be a confounding factor in their study as play behavior decreases with age. Only one study investigated lying time during the post-weaning period and found no effect of weaning age.

There is some evidence (2 of 3 studies) indicating that weaning at later ages reduces signs of hunger, measured as frequency of vocalizations and unrewarded visits to the milk feeder. Calves weaned at 8 wk spent less time vocalizing around weaning than calves weaned at 6 wk (Eckert et al., 2015), and calves weaned at 13 wk had fewer unrewarded visits to the milk feeder during and the week after weaning compared with calves weaned at 7 wk (de Passillé and Rushen, 2016). These behavioral indicators of reduced hunger are likely a result of the corresponding greater starter intake during weaning and post-weaning in these calves that were weaned at later ages. Furthermore, the effect of weaning age on visits to the milk feeder was dependent upon milk allowances; calves weaned at 7 wk and fed 6 L/d had a greater number of visits during weaning than calves weaned at 7 wk and fed 12 L/d and calves weaned at 13 wk and fed 12 L/d (de Passillé et al., 2011b). The week after weaning, calves weaned at 7 wk and fed 12 L/d had a greater number of visits compared with calves weaned at 7 wk and fed 6 L/d, and calves weaned at 13 wk and fed 12 L/d (de Passillé et al., 2011b). This suggests that earlier weaning ages elevate unrewarded visits, but more so during weaning for calves fed low milk allowances, and more so after weaning for calves fed higher milk allowances. Unfortunately, within this study rewarded and unrewarded visits were combined, making interpretation of results difficult; however, rewarded visits (with milk) are unlikely to have increased during weaning, so it is the unrewarded visits (without milk) that are most likely to have increased at this time. Overall, there appears to be some evidence suggesting that calves weaned at later ages show fewer signs of hunger around weaning; however, there remains too few studies to generate strong conclusions regarding the impact of weaning age on behavioral indicators of hunger.
### Table 1. Studies (n = 16) investigating the effect of weaning age on starter intake (n = 12) and growth (n = 16) in dairy calves

<table>
<thead>
<tr>
<th>Reference</th>
<th>Weaning age treatment</th>
<th>N</th>
<th>Breed</th>
<th>Housing (group size)</th>
<th>Milk allowance</th>
<th>Observational period</th>
<th>Outcome variable</th>
<th>Methods</th>
<th>Effect2</th>
<th>Experimental Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heinrichs et al. (1990)</td>
<td>28 d; 49 d</td>
<td>44 HF</td>
<td></td>
<td>Individual</td>
<td>4 L/d</td>
<td>Overall: 1 to 56 d</td>
<td>Starter Intake</td>
<td>Intake and BW measured weekly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>de Passillé et al. (2011)</td>
<td>48 d (fed 6 L/d); 48 d (fed 12 L/d); 89 d (fed 12 L/d)</td>
<td>44 HF</td>
<td>(9)</td>
<td>Group</td>
<td>6 L/d; 12 L/d</td>
<td>Overall: 1 to 90 d</td>
<td>Starter Intake</td>
<td>Intake measured daily by AMF. BW measured weekly</td>
<td>-/+3</td>
<td></td>
</tr>
<tr>
<td>Bjorklund et al. (2013)</td>
<td>47.6 d; 64.5 d; 93.7 d</td>
<td>124 HF, HMS, HJS</td>
<td>Group (10)</td>
<td>4.4 L/d</td>
<td>Overall: 1 to 90 d</td>
<td>Final BW taken on 140 d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meake et al. (2015)</td>
<td>56 d; 70 d; 84 d</td>
<td>112 HF</td>
<td></td>
<td>Individual</td>
<td>8 L/d</td>
<td>Overall: 28 to 91 d</td>
<td>Intake measured daily by AMF</td>
<td>Final BW measured every second day</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Eckert et al. (2015)</td>
<td>42 d; 56 d</td>
<td>20 HF</td>
<td></td>
<td>Individual</td>
<td>8 L/d</td>
<td>Overall: 21 to 91 d</td>
<td>Intake measured daily by AMF. BW measured weekly</td>
<td>+/+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>de Passillé and Rushen (2016)</td>
<td>48 d; 89 d</td>
<td>56 HF</td>
<td></td>
<td>Group (5 to 9)</td>
<td>12 L/d</td>
<td>Overall: 1 to 120 d</td>
<td>Intake measured daily. BW measured monthly. Final BW taken on 130 d</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zahmatkesh et al. (2018)</td>
<td>63 d; 84 d</td>
<td>60 HF</td>
<td></td>
<td>Individual</td>
<td>7 L/d</td>
<td>Overall: 1 to 84 d (starter intake)</td>
<td>Starter Intake</td>
<td>Final BW measured weekly</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Dennis et al. (2018)</td>
<td>42 d; 52 d</td>
<td>96 HF</td>
<td></td>
<td>Individual</td>
<td>4.7 L/d; 7.8 L/d</td>
<td>Overall: 1 to 56 d</td>
<td>Starter Intake</td>
<td>Final BW measured weekly</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Johnson et al. (2018)</td>
<td>37 to 97 d (mean (±SD) across 11 farms: 64.3 ± 9.4 d)</td>
<td>492 HF, VR, AY</td>
<td>Individual; Paired; Group (3 to 20)</td>
<td>4 to 7 L/d</td>
<td>Overall: 1 to 63 d</td>
<td>Starter Intake</td>
<td>Final BW measured weekly</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McCaull et al. (2019)</td>
<td>56 d; 91 d</td>
<td>16 HF</td>
<td></td>
<td>Group (5)</td>
<td>4 L/d</td>
<td>Overall: 8 to 100 d</td>
<td>Starter Intake</td>
<td>Intake measured weekly. Final BW taken at 140 d</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Schwarzkopf et al. (2019)</td>
<td>49 d; 119 d</td>
<td>59 HF</td>
<td></td>
<td>Group (Not specified)</td>
<td>9 L/d</td>
<td>Overall: 8 to 149 d</td>
<td>Final BW</td>
<td>AMF. BW measured on 1, 26, 42, 70, 98, 112, and 140 d. Final BW taken at 140 d</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Seifzadeh et al. (2019)</td>
<td>42 d; 63 d; 84 d</td>
<td>30 HF</td>
<td>Not Specified</td>
<td>6 L/d</td>
<td>Overall: 1 to 84 d</td>
<td>Starter Intake</td>
<td>Final BW measured bi-weekly. Final BW measured weekly</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costigan et al. (2022)</td>
<td>56 d; 84 d</td>
<td>187 HF, JE</td>
<td>Group (20)</td>
<td>6 L/d</td>
<td>Overall: 1 to 84 d</td>
<td>Starter Intake</td>
<td>Final BW measured by AMF. BW measured on 1, 26, 42, 70, 98, 112, and 140 d. Final BW taken at 140 d</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferronato et al. (2022)</td>
<td>45 d; 60 d</td>
<td>10 SI</td>
<td></td>
<td>Individual</td>
<td>6 L/d</td>
<td>Days relative to weaning: −25, −15, 0, 6, and 20 d</td>
<td>Starter Intake ADG</td>
<td>Final BW measured bi-weekly. Final BW measured weekly. Final BW measured at 84 d</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Rahimi et al. (2023)</td>
<td>50 d; 75 d</td>
<td>48 HF</td>
<td></td>
<td>Individual</td>
<td>7 L/d</td>
<td>Overall: 1 to 90 d</td>
<td>Starter Intake ADG</td>
<td>Intake measured daily. BW measured 20 d after weaning</td>
<td>+</td>
<td></td>
</tr>
</tbody>
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Continued
Table 1 (Continued). Studies (n = 16) investigating the effect of weaning age on starter intake (n = 12) and growth (n = 16) in dairy calves.

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<thead>
<tr>
<th>Reference</th>
<th>Weaning age treatment</th>
<th>N</th>
<th>Breed</th>
<th>Housing (group size)</th>
<th>Milk allowance</th>
<th>Observational period</th>
<th>Outcome variable</th>
<th>Methods</th>
<th>Effect 2</th>
<th>Experimental Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolfe et al. (2023)</td>
<td>42 to 49 d; 56 - 63 d</td>
<td>72</td>
<td>HF</td>
<td>Individual</td>
<td>12 L/d</td>
<td>Wean: early-abrupt: 39 - 42 d; early-gradual: 35 - 49 d; late-abrupt: 53 - 56 d; late-gradual: 49 - 63 d</td>
<td>Starter Intake</td>
<td>Intake measured daily; BW measured weekly.</td>
<td>=</td>
<td>—</td>
</tr>
</tbody>
</table>

1HF = Holstein; HMS = crossbreed of Holstein, Montbeliarde, and Swedish Red; HJS = crossbreed of Holstein, Jersey, and Swedish Red; VR = Viking Red cross; AY = Ayrshire; SI = Simmental.

2Effects are presented for older weaning ages with respect to younger weaning ages. Effect direction: “+” indicates that the effect was interpreted as positive or desirable; “−” as negative or undesirable, and “+/−” as mixed or unclear. Studies are ordered chronologically by year.

3Effects dependent on milk allowance.

4Initially, calves were to be weaned at 30, 60, and 90 d of age; however, due to intake criteria of weaning (1 kg/d of starter to complete weaning) variable weaning ages of 47.6, 64.5, and 93.7 d of age were seen.

5Calves weaned at 64 d had lower Final BW compared with calves weaned at 47 d and 93 d.

6Additional treatment of corn processing method (steam-flaked vs. ground). Calves fed steam-flaked corn in their starter and weaned at 75 d had greater starter intake over the experimental period (1 to 90 d) compared with calves fed steam-flaked corn and weaned at 50 d and calves fed ground corn and weaned at 50 d or 75 d.

7Additional treatment assessing weaning duration (see Table 3 for weaning duration results). Treatments were assigned in a 2 × 2 factorial assignment of weaning age (early 42 to 49 d vs. late 56 to 63 d) and weaning duration (abrupt 3 d vs. gradual 14 d). Treatments were as followed: early-abrupt: 3 d duration and weaned at 42 d; early-gradual: 14 d duration and weaned at 49 d; late-abrupt: 3 d duration and weaned at 56 d; late-gradual: 14 d duration and weaned at 63 d.
Table 2. Studies (n = 6) investigating the effect of weaning age on behavior of dairy calves.1

<table>
<thead>
<tr>
<th>References</th>
<th>Weaning Age Treatment</th>
<th>Housing N (group size)</th>
<th>Milk allowance</th>
<th>Observational period</th>
<th>Outcome variable2</th>
<th>Methods</th>
<th>Effect3</th>
<th>Experimental Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krachun et al. (2010)</td>
<td>48 d (fed 6 L/d); 48 d (fed 12 L/d); 89 d (fed 12 L/d)</td>
<td>44 Group (9)</td>
<td>6 L/d; 12 L/d</td>
<td>Weeks of age: 3, 5, 7, 9, 11, 13, and 14 wk</td>
<td>Locomotor play</td>
<td>Behavior recorded (video) from 0800 h to 2400 h for 2 d/wk over the observational period, yielding 32 h/wk of observations/calf</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>de Passillé et al. (2011b)</td>
<td>48 d (fed 6 L/d); 48 d (fed 12 L/d); 89 d (fed 12 L/d)</td>
<td>44 Group (9)</td>
<td>6 L/d; 12 L/d</td>
<td>Weeks relative to weaning: 0 and 1 wk</td>
<td>URV4</td>
<td>Visits recorded daily by AMF</td>
<td>+/-4</td>
<td></td>
</tr>
<tr>
<td>de Passillé et al. (2011a)</td>
<td>48 d (fed 6 L/d); 48 d (fed 12 L/d); 89 d (fed 12 L/d)</td>
<td>44 Group (9)</td>
<td>6 L/d; 12 L/d</td>
<td>Weeks of age: 5, 7, 9, 13, and 14 wk</td>
<td>CS</td>
<td>Behavior recorded (video) in 6, 2-h blocks from 0600 h to 2400 h for 2 d/wk over the observational period, yielding 24 h/wk of observations/calf.</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Eckert et al. (2015)</td>
<td>42 d; 56 d</td>
<td>20 Individual</td>
<td>8 L/d</td>
<td>Weeks relative to weaning: -2, -1, 0, 1, 2 wk</td>
<td>NNPen/OtherOralLying time</td>
<td>Behavior recorded (live) from 1500 h to 1600 h for 3 d/wk over the observational period using instantaneous sampling at 1 min intervals, yielding 3 h/wk of observations/calf.</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>de Passillé and Rushen (2016)</td>
<td>48 d; 89 d</td>
<td>56 Group (5 to 9)</td>
<td>12 L/d</td>
<td>Weeks relative to weaning: 1, 0, 1, 2 wk</td>
<td>URV</td>
<td>URV recorded daily by AMF</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Rahimi et al. (2023)</td>
<td>50 d; 75 d</td>
<td>48 Individual</td>
<td>7 L/d</td>
<td>Post-wean: 75 to 77 d</td>
<td>NNPen/OtherOralLying time</td>
<td>Behavior recorded from 0800 to 1600 h for 3 d consecutively, yielding 8 h total observation/calf.</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

1All Studies used Holstein calves.

2CS = cross-sucking, NNPen = non-nutritive sucking on pen fixtures, OtherOral = other oral behaviors such as licking and biting. URV = unrewarded visits at the milk feeder.

3Effects are presented for older weaning ages with respect to younger weaning ages. Effect direction: “+” indicates that the effect was interpreted as positive or desirable, “−” as negative or undesirable, and “+/−” as mixed or unclear. Studies are ordered chronologically by year.

4Study used both unrewarded and rewarded visits. Results dependent on milk allowance where calves weaned at 48 d fed 6 L/d had greater number of visits during weaning compared with calves weaned at 48 d fed 12 L/d and 89 d fed 12 L/d. The week after weaning, calves weaned at 48 d fed 12 L/d had a greater number of visits compared with calves weaned at 48 d fed 6 L/d and 89 d fed 12 L/d.
Weaning Duration

Weaning durations were investigated across 13 studies, with 10 studies measuring feed intake and growth, 4 studies measuring behavior, and 4 studies measuring health. Most studies (n = 11) experimentally compared shorter vs. longer weaning durations. The range of ‘shorter’ durations included 1 d (n = 7), 3 d (n = 1), 7 d (n = 2), and 11 d (n = 1); while the range of ‘longer’ durations included 12 d (n = 1), 14 d (n = 3), 19 d (n = 1), 21 to 22 d (n = 5), and 35 d (n = 1). The remaining 2 studies used a cross-sectional study design with varying weaning durations across farms.

Feed Intake and Growth. All studies investigating weaning duration on feed intake and growth (n = 10) assessed starter intake (see Table 3 for summary of effects). Six studies reported results for the weaning period while 5 studies reported results for the post-weaning period. During weaning, 3 studies found a positive effect of longer weaning duration on starter intake while 2 studies found no effect and 1 study found a negative effect. It is important to note that the study that found a negative effect of longer weaning duration on starter intake during weaning (Welk et al., 2022) only reported results for the week after weaning was initiated, so calves on the longer weaning duration treatment were much younger (35 d vs 49 d) when starter intake was measured. This is an interesting finding and supports results found on weaning age that older calves can consume greater amounts of solid feed during weaning compared with their younger counterparts (de Passillé et al., 2011b; Eckert et al., 2015). Post-weaning, 3 studies found a positive effect of longer weaning durations on starter intake while 2 studies found no effect. Four studies reported results over the experimental period, with 3 studies finding a positive effect of longer weaning durations while 1 study found no effect. One explanation for these mixed findings could be the milk allowance. Bittar et al. (2020) fed calves 4 L/d and found no difference in starter intake during weaning and post-weaning between calves weaned abruptly versus over 21 d; these authors concluded that gradual weaning does not improve starter intake and may not be necessary in calves fed low milk allowances. Three studies employed a 2 × 2 factorial study design to assess interactions of milk allowance and weaning duration, but none reported that these interactions impacted starter intake, regardless of weaning period (Nielsen et al., 2008a; Dennis et al., 2018; Klopp et al., 2019). The remaining 6 studies assessing the effect of weaning duration on starter intake fed a range of milk allowances between 6 and 12 L/d; all found a positive effect of longer weaning durations on starter intake, regardless of weaning period. These results do not necessarily mean that overall starter intake does not depend on both milk allowance and weaning duration; indeed, it is known that initiating milk removal stimulates starter intake, especially when done early and at low milk allowances (Khan et al., 2016). Rather, it is likely that different combinations of milk allowance and weaning duration stimulate starter intake earlier or later, but overall leading to similar total starter intake. This is a knowledge gap that remains to be explored.

All studies investigating the effects of weaning duration on feed intakes and growth reported ADG (n = 10) while 8 studies reported final BW (see Table 3 for summary of effects). Overall, results were mixed. In terms of ADG, 6 studies reported results over the weaning period and 5 studies reported over the post-weaning period. During weaning, 3 studies found a positive effect of longer weaning duration on ADG while 1 study found no effect and 2 studies found a negative effect. Post-weaning, 2 studies found a positive effect of longer weaning duration on ADG while 3 studies found no effect. Four studies reported results over the experimental period and all studies found no effect of weaning duration on ADG. In terms of final BW, 4 studies reported results over the weaning and post-weaning period. During weaning, 1 study found no effect of weaning duration on final BW while 2 studies found a negative effect. Post-weaning, all 3 studies found no effect of weaning duration on final BW. One study found a mixed effect of weaning durations on final BW both during and after weaning; Sweeney et al. (2010) found that calves weaned abruptly and over 10 d had greater final BW at weaning and 1 wk post-weaning compared with calves weaned over 4 d and 22 d. Four studies reported results over the experimental period and all found no effect of weaning duration on final BW.

There appears to be no clear benefit nor downside of longer weaning durations on calf growth. Studies finding negative effects of longer weaning durations on growth during the weaning period often compared abrupt weaning to gradual weaning (Sweeney et al., 2010; Steele et al., 2017) or days relative to weaning initiation (Welk et al., 2022). This can be an unfair comparison as calves weaned abruptly have not yet had their milk reduced or removed. In addition, several studies reported final BW within 7 d of weaning (Steele et al., 2017; Dennis et al., 2018; Klopp et al., 2019; Sweeney et al., 2019), which potentially misses the growth check in calves that are weaned abruptly or over short periods. Notably, there were no studies that found a negative effect of longer weaning durations on post-weaning growth, which would suggest that, as predicted, longer weaning durations may prevent or reduce a growth check at weaning.
Table 3. Studies (n = 10) investigating the effect of weaning duration on starter intake and growth of dairy calves

<table>
<thead>
<tr>
<th>Reference</th>
<th>Weaning Duration Treatment</th>
<th>N Breed</th>
<th>Housing (group size)</th>
<th>Milk allowance L/d</th>
<th>Weaning age</th>
<th>Observational period</th>
<th>Outcome variable</th>
<th>Methods</th>
<th>Effect2</th>
<th>Experimental Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nielsen et al. (2008a)</td>
<td>1 d; 14 d</td>
<td>72 HF, DR, JER</td>
<td>Group (12)</td>
<td>4.8; 9.2</td>
<td>56 d</td>
<td>Wean: 42 to 55 d. Post-Wean: 46 to 61 d.</td>
<td>Starter Intake: ADG measured daily by AMF. BW measured weekly.</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Sweeney et al. (2010)</td>
<td>1 d; 4 d; 10 d; 22 d</td>
<td>40 HF</td>
<td>Group (4)</td>
<td>12</td>
<td>41 d</td>
<td>Wean: 19 to 40 d. Post-Wean: 41 to 49 d.</td>
<td>Starter Intake: ADG measured daily by AMF. BW measured weekly. Final BW taken on 45 and 49 d.</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Steele et al. (2017)</td>
<td>1 d; 12 d</td>
<td>54 HF</td>
<td>Individual</td>
<td>9</td>
<td>49 d</td>
<td>Wean: 37 to 48 d. Post-Wean: 49 to 54 d.</td>
<td>Starter Intake: ADG measured daily. BW measured every 6 d. Final BW taken at 48 and 54 d.</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Dennis et al. (2018)</td>
<td>7 d; 14 d</td>
<td>96 HF</td>
<td>Individual</td>
<td>4.7; 7.8</td>
<td>42 d; 52 d</td>
<td>Overall: 1 to 56 d</td>
<td>Starter Intake: ADG. BW measured every 6 d. Final BW taken at 56 d.</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Klopp et al. (2019)</td>
<td>7 d; 21 d</td>
<td>50 HF</td>
<td>Individual</td>
<td>4.7; 7.9</td>
<td>49 d</td>
<td>Overall: 1 to 56 d</td>
<td>Starter Intake: ADG measured daily. BW measured on 14, 21, 28, 35, 42, 49, and 56 d. Final BW taken at 56 d.</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Scoley et al. (2019)</td>
<td>1 d; 21 d</td>
<td>90 HF</td>
<td>Group (15)</td>
<td>6</td>
<td>50 d; 56 d</td>
<td>Overall: 1 to 62 d</td>
<td>Starter Intake: ADG measured daily by AMF. Half weight measured daily by automated scale. Final BW taken at 62 d.</td>
<td>—</td>
<td>—</td>
<td>=</td>
</tr>
<tr>
<td>Bittar et al. (2020)</td>
<td>1 d; 21 d</td>
<td>36 HF</td>
<td>Individual</td>
<td>4</td>
<td>56 d</td>
<td>Wean: 36 to 56 d. Post-Wean: 57 to 70 d.</td>
<td>Starter Intake: ADG measured daily. BW measured weekly. Final BW at 56 and 70 d. Intake measured daily. BW measured every 10 d.</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Mirzaei et al. (2020)</td>
<td>1 d; 7 d; 14 d; 35 d</td>
<td>48 HF</td>
<td>Individual</td>
<td>8</td>
<td>63 d</td>
<td>Overall: 3 to 80 d</td>
<td>Starter Intake: ADG measured daily. BW measured every 10 d. Final BW taken at 80 d.</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Wolfe et al. (2023)</td>
<td>3 d; 14 d</td>
<td>72 HF</td>
<td>Individual</td>
<td>12</td>
<td>42 d; 49 d; 56 d; 63 d</td>
<td>Wean: early-abrupt: 39 to 42 d; early-gradual: 35 to 49 d; late-abrupt: 53 to 56 d; late-gradual: 49 to 63 d</td>
<td>Starter Intake: ADG measured daily. BW measured weekly.</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
</tbody>
</table>

1HF = Holstein; DR = Danish Red; JER = Jersey.
2Effects are presented for longer weaning durations with respect to shorter weaning durations. Effect direction: “+” indicates that the effect was interpreted as positive or desirable, “−” as negative or undesirable, and “−/+” as mixed or unclear. Studies are ordered chronologically by year.
3Different weaning ages for treatments were due to the intake criteria of weaning. Calves weaned over 19 d had milk allowance abruptly reduced to 3 L/d at 35 d while calves weaned over 11 d had milk allowance abruptly reduced to 3 L/d at 49 d. All calves were required to consume 1.0 kg of starter to complete weaning.
4Additional treatment assessing weaning age (see Table 1 for weaning age results). Treatments were assigned in a 2 × 2 factorial design of weaning age (early 42 to 49 d vs. late 56 to 63 d) and weaning duration (abrupt 3 d vs. gradual 14 d). Treatments were as followed: early-abrupt: 3 d duration and weaned at 42 d; early-gradual: 14 d duration and weaned at 49 d; late-abrupt: 3 d duration and weaned at 56 d; late-gradual: 14 d duration and weaned at 63 d.
Another explanation for the lack of growth difference depending on weaning duration is the age of calves when weaning is initiated and completed. Most studies (8 out of 10 studies) completed weaning at ≤8 wk of age. As previously discussed, calves weaned at younger ages are not able to consume as much starter during weaning as their older counterparts (de Passillé et al., 2011b; Eckert et al., 2015). Due to younger weaning ages selected, calves with greater weaning duration had weaning initiated at very young age. For example, Sweeney et al. (2010) initiated weaning at 19 d of age for calves on the 22-d weaning duration treatment. Currently, the age at which weaning should be initiated is unknown and not often discussed in the literature. However, based on results from Wickramasinghe et al. (2022), initiating weaning at 35 d appears to be too early as this reduced starter intake and ADG in the first week of weaning compared with initiating weaning at 49 d. Future research should consider age of weaning initiation, weaning age, and weaning duration together. 

**Behavior.** Few studies (n = 4) investigated the effects of weaning duration on behavior (see Table 4 for summary of effects). Three studies measured oral behaviors (cross-sucking: n = 2; non-nutritive sucking at the teat: n = 1; other oral behavior such as licking and biting: n = 1). The 2 studies assessing cross-sucking during weaning found longer weaning durations increased cross-sucking. Both studies compared abrupt to gradual weaning; thus, abruptly weaned calves would not have experienced any milk removal during their classified weaning period. Post-weaning, 1 study found that longer weaning durations reduced cross-sucking while 1 study found no effect. One potential reason for the difference between these studies is the number of days that behaviors were recorded (e.g., 3 d post-weaning in Nielsen et al. (2008a); 7 d post-weaning in de Passillé et al. (2010)). It is also important to note that the 2 studies measuring cross-sucking used automated milk feeders. A possible downside to longer weaning durations when using automated feeders is that daily milk allowance and meal size becomes very low toward the end of the weaning period, especially if pre-weaning milk allowance is already restricted. Small meal sizes are likely to lead to hunger and elicit sucking motivation (de Passillé et al., 1992; Rushen and de Passillé, 1995). This could explain why the 2 studies found more cross-sucking in calves experiencing longer weaning durations, and especially when there is competition for the feeder (Jensen, 2003). Only 1 study looked at lying time and found a positive effect of longer weaning durations on lying time during weaning, but no effect post-weaning; this may occur when calves reduce their visits to the milk feeder as milk is increasingly removed during weaning. 

All 4 studies assessed behavioral signs of hunger. It was predicted that longer weaning durations should reduce hunger. However, the 2 studies that measured vocalizations found no differences between weaning duration treatments and the 2 studies that measured unrewarded visits to the milk feeder found mixed results. Both Nielsen et al. (2008a) and Scoley et al. (2019) found that calves weaned over 14 or 21 d, respectively, compared with abruptly weaned, had a greater number of unrewarded visits during weaning (in the period before calves were abruptly weaned). However, these studies found contrasting results for the post-weaning period, where calves weaned over 14 d had fewer unrewarded visits post-weaning (Nielsen et al., 2008a), while calves weaned over 21 d had greater unrewarded visits post-weaning (Scoley et al., 2019). It is important to note that the post-weaning period in the latter study began the day that gradual weaned calves were weaned, but began 5 d after abrupt calves were weaned (thus, the steep peak in unrewarded visits for abruptly weaned calves occurring in the first 2 d after weaning was not reflected in the reporting period Scoley et al. (2019)). Overall, these mixed results were not consistent with our prediction that longer weaning durations (i.e., gradual weaning) reduces behavioral signs of hunger. The mixed results are likely related to how weaning and post-weaning periods were defined and the timing of when behaviors were measured. 

**Weaning Criteria**

Weaning criteria were investigated across 9 studies, with 5 studies measuring feed intake and growth, 7 studies measuring behavior, and 2 studies measuring health. Five studies compared intake-based weaning (initial intake targets tested included: 200, 225, and 700 g/d; final intake targets tested included: 1150, 1300, 1400, and 2000 g/d) to age-based weaning (ages tested included: 48, 56, 70, 84, and 88 d of age). Two studies explored different intake criteria for initiating and completing weaning when weaning by intake (initial intake targets: 200 vs. 400 g/d; final intake targets: 800 vs. 1600 g/d). The final study was a cross-sectional study and had age, starter intake, visual assessment, and weight as listed weaning criteria. Five studies investigated the effects of intake-based weaning compared with age-based weaning on starter intake and growth (see Table 5 for summary of effects). Of the 4 studies that measured starter intake, all studies found a positive effect of intake-based weaning on starter intake during weaning; in the post-weaning period, 2 studies found no effect and one study found a positive effect on starter intake. Results on growth were mixed. Three studies found a positive effect of...
intake-based weaning on ADG during weaning and post-weaning while 2 studies found no effect. Only 3 studies reported final BW with one study finding a positive effect while another study found no effect of intake-based weaning. One study found that the effect was dependent on weaning age. de Passillé and Rushen (2016) found that calves weaned by intake had greater final BW compared with calves weaned at 7 wk, but similar final BW to calves weaned at 13 wk. Similar to de Passillé and Rushen (2016), calves weaned at 8 wk in Whalin et al. (2022) had lower growth compared with the intake-based weaning treatment, while both Benetton et al. (2019) and Roth et al. (2009) found no differences in growth when calves were weaned at later weaning ages (10 wk and 12 wk, respectively) compared with the intake-based weaning treatment. Another explanation for the mixed results regarding growth could be the observation period. Benetton et al. (2019) controlled for age by reporting results in set periods regardless of the variable weaning ages in the intake-based treatment, while the remaining studies reported results relative to the calves’ weaning age. Overall, weaning based on starter intake had no negative effect on growth and improved starter intake, suggesting that this weaning approach may be beneficial, especially for calves that need more time to begin eating starter before milk is removed.

All 5 studies investigating intake-based weaning assessed behavior. Four studies assessed unrewarded visits to the milk feeder with mixed results. Benetton et al. (2019) and Welk et al. (2022) had similar experimental designs in the same facility, and both found that calves weaned by intake had a greater number of unrewarded visits during weaning but fewer after weaning, compared with calves weaned at 10 wk. In contrast, Whalin et al. (2022) found no difference in unrewarded visits between calves weaned by intake versus weaned at 8 wk. Together these 3 studies provide further support that weaning age plays a role in unrewarded visits. Indeed, de Passillé and Rushen (2016) found that calves weaned by intake had fewer unrewarded visits during and after weaning compared with calves weaned at 7 wk, but had a similar number of unrewarded visits compared with calves weaned at 12 wk. Only one study (Roth et al., 2008) assessed cross-sucking and found that fewer calves weaned by intake performed cross-sucking in the post-weaning period compared with calves weaned at 12 wk. Overall, our understanding of behavior of calves weaned based on starter intake versus age remains scarce, but a general consensus from unrewarded visits suggests that calves may still experience hunger or frustration even when weaned based on their starter intake. This may be related to the abrupt reductions in milk when intake targets are reached, or due to low daily milk allowance in the period before reaching the final intake target. For instance, some authors (Benetton et al., 2019; Whalin et al., 2022; Welk et al., 2022) described daily milk allowance for some calves was just 1 L/d in the final days before complete weaning, which likely promoted more unrewarded visits in attempts to retrieve more milk. Unrewarded visits and cross-sucking are viewed as a behavioral indicator of hunger and frustration (Jensen and Holm, 2003; De Paula Veira et al., 2008), so future development of weaning programs should aim to minimize these behaviors. For example, higher target solid feed intakes may reduce unrewarded visits if calves are more established on solid feed before a portion of milk is removed, or a single milk portion may be better to deliver the final low milk allowances than several very small portions.

Two studies investigated different intake criteria when weaning by starter intake (de Passillé et al., 2012; Miguel-Pacheco et al., 2015). Within these studies, 2 starter intake targets for initiating weaning (200 vs. 400 g/d) and 2 targets for completing weaning (800 vs 1600 g/d) were investigated and applied in 2 × 2 factorial design. Over the experimental period (20 to 87 d of age) no effects were observed between treatments on ADG, final BW at 87 d, overall starter intake or play behavior. However, initiating weaning at 200 g/d resulted in a greater number of unrewarded visits to milk feeder. In addition, during the actual period of weaning (from the first day that milk allowance was reduced to the last day that each calf received milk), using the 1600 g/d target for completing weaning resulted in increased ADG. It is important to note that calves with low initiating starter targets (i.e., 200 g/d) had longer weaning durations and calves with high completing targets (i.e., 1600 g/d) weaned at later ages. Greater weaning durations were positively correlated with final BW at 87 d, ADG, starter intake, but also positively correlated with unrewarded visits to the feeder over the experimental period. Overall, the choice of intake targets for intake-based weaning approaches requires more research to fully understand how low versus high initial and final intake targets affect calf behavior and performance.

Our search criteria revealed no studies that examined the effects of weaning based on weight, which is surprising given this is cited as a weaning method by farmers (e.g., 21% of USA farmers (USDA-NAHMS, 2014); 35% of Irish farmers (Sinnott et al., 2023); 20 to 30% of UK farmers (Mahendren et al., 2022); 24% of Australian farmers (Aleri et al., 2022)). However, these survey studies all mentioned that farmers often did not actually weigh their calves, relying on observation to make a weaning determination. Doubling of birth weight was cited by farmers as one way to wean calves in an
<table>
<thead>
<tr>
<th>References</th>
<th>Weaning Duration Treatment</th>
<th>Housing (group size)</th>
<th>Milk allowance</th>
<th>Weaning age</th>
<th>Observational period</th>
<th>Outcome variable$^2$</th>
<th>Methods</th>
<th>Effect$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nielsen et al. (2008a)</td>
<td>1 d; 14 d</td>
<td>Group (12) 4.8 L/d; 9.256 d L/d</td>
<td></td>
<td></td>
<td>Wean: 42 to 55 d. Post-Wean: 56 to 61 d.</td>
<td>CS NNTeat$^4$</td>
<td>URV</td>
<td>- +</td>
</tr>
<tr>
<td>de Passillé et al. (2010)</td>
<td>1 d; 4 d; 10 d; 40</td>
<td>Group (4) 12 L/d</td>
<td>42 d</td>
<td></td>
<td>Wean: 19 to 41 d. Post-Wean: 42 to 49 d.</td>
<td>CS Vocalizations</td>
<td></td>
<td>= =</td>
</tr>
<tr>
<td>Scoley et al. (2019)</td>
<td>1 d; 21 d</td>
<td>Group (15) 6 L/d</td>
<td>50 d; 56 d$^5$</td>
<td></td>
<td>Wean period 1: 42 to 49 d. Wean period 2: 50 to 56 d. Post-Wean: 57 to 62 d.</td>
<td>Lying time</td>
<td>URV</td>
<td>Period 1: -Period 2: =</td>
</tr>
<tr>
<td>Bittar et al. (2020)</td>
<td>1 d; 21 d</td>
<td>Individual 4 L/d</td>
<td>56 d</td>
<td></td>
<td>Days relative to weaning: on −14, −7, −2, 0, 2, and 7 d</td>
<td>OtherOral Vocalizations</td>
<td></td>
<td>= =</td>
</tr>
</tbody>
</table>

$^1$All studies used Holstein calves.

$^2$CS = cross-sucking; NNTeat = non-nutritive sucking at the teat; URV = unrewarded visits at the milk feeder; OtherOral = other oral behaviors such as licking and biting.

$^3$Effects are presented for longer weaning durations with respect to shorter weaning durations. Effect direction: “+” indicates that the effect was interpreted as positive or desirable, “−” as negative or undesirable, and “-/+” as mixed or unclear. Studies are ordered chronologically by year.

$^4$NNTeat was considered the amount of time a calf spent in the milk feeder after milk was fully consumed.

$^5$To control the total milk fed, calves on the abrupt weaning treatment were weaned at 50 d of age while calves weaned over 21 d were weaned at 56 d of age.
Weaning methods (linear or step-down) encourage solid feed intake and growth. One interesting finding from Welboren et al. (2019) was calves on the dynamic step-down method (where milk reduction at each step was based on the calf’s average milk intake) had greater post-weaning ADG and final BW compared with calves on the linear reduction and the ‘fixed’ step-down weaning method (where the calf’s initial milk reduction was abruptly reduced from ab libitum (approx. Ten L/d) to 6 L/d). This result suggests that large drops in milk in a gradual weaning method may affect performance and should be avoided when designing weaning programs.

Finally, one study examined reduced meal size and/or frequency as a weaning method. Jensen (2006) compared calves that were weaned by reducing meal size (number of meals/d remained consistent but meal size decreased) versus calves that were weaned by reducing both the number of meals/d and meal size. No difference in starter intake or ADG were found between treatments; however, calves weaned by reducing meal size had fewer unrewarded visits at the milk feeder. This is a notable finding as it has been previously suggested that the method of milk reduction by automated feeders may be a source of frustration for calves during weaning (Welk et al., 2022). Reducing meal size but keeping the number of meals/d consistent may eliminate the uncertainty of when the next meal will be available from the automated feeder, potentially alleviating frustration around weaning. Currently, there is little understanding on how meal size, meal frequency, or minimum milk allowance affects the weaning transition. Studies examining meal frequency during the pre-weaning period have found that many meals with small portions of milk stimulate sucking motivation (Rushen and de Passillé, 1995; Jensen et al., 2020). This may increase the risk of cross-sucking, especially during weaning when milk allowances are low and meal sizes are very small. As discussed above, very low milk allowance may have led to greater unrewarded visits to the milk feeder in calves weaned based on starter intake, raising the question about the appropriate minimum milk allowance during weaning. In addition, calves offered fewer milk meals spend more time consuming concentrate (Jensen et al., 2020) suggesting that fewer but larger meals during weaning may be more beneficial for transitioning calves onto solid feed. Overall, the number of meals and meal size that calves are offered during weaning should be taken into consideration, but the optimal number of meals or meal size has yet to be investigated. Future research should disentangle these effects and determine their impact on abnormal oral behaviors and hunger in dairy calves.
Table 5. Studies (n = 5) investigating the effect of intake-based weaning (compared with age-based weaning) on behavior and performance of dairy calves

<table>
<thead>
<tr>
<th>Reference</th>
<th>Weaning criteria treatment</th>
<th>N</th>
<th>Breed</th>
<th>Housing (group size)</th>
<th>Milk allowance</th>
<th>Observational period</th>
<th>Outcome variable</th>
<th>Methods</th>
<th>Wean</th>
<th>Post-Wean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roth et al. (2008)</td>
<td>Wean by age at 84 d; Wean by intake (targets: 700, 2000 g/d)</td>
<td>27 BS</td>
<td>Pair</td>
<td>6 L/d</td>
<td>Wean: characterized by reduction in milk Post-wean: 14 d after complete milk removal</td>
<td>ADG</td>
<td>CS</td>
<td>BW measured at the start and end of each observational period. CS recorded (video) 1 wk before weaning and 1 wk after weaning for 2 d from 0600 h to 2100 h, yielding 30 h/wk of observations/calf.</td>
<td>+</td>
<td>=</td>
</tr>
<tr>
<td>de Passille and Rushen (2016)</td>
<td>Wean by age at 48 or 88 d; Wean by intake (targets: 200, 600, 1000, 1400 g/d)</td>
<td>56 HF</td>
<td>Group (5 to 9)</td>
<td>12 L/d</td>
<td>Wean: characterized by reduction in milk Post-wean: 14 d after complete milk removal</td>
<td>Starter Intake ADG</td>
<td>Daily by AMF, BW measured</td>
<td>+</td>
<td>+/−/−</td>
<td></td>
</tr>
<tr>
<td>Benetton et al. (2019)</td>
<td>Wean by age at 70 d; Successfully wean by intake (targets: 225, 675, 1300 g/d)</td>
<td>32 HF</td>
<td>Group (8)</td>
<td>12 L/d</td>
<td>Wean: 31 to 69 d. Post-wean: 70 to 98 d</td>
<td>Starter Intake ADG Final BW URV</td>
<td>BW measured weekly. Final BW taken at 91 d.</td>
<td>=</td>
<td>=</td>
<td></td>
</tr>
<tr>
<td>Whalin et al. (2022)</td>
<td>Wean by age at 56 d; Successfully wean by intake (targets: 225, 675, 1300 g/d)</td>
<td>30 NR</td>
<td>Group (3 to 5)</td>
<td>12 L/d</td>
<td>Wean: 31 d to complete milk removal. Post-wean: 20 d after complete milk removal</td>
<td>Starter Intake ADG URV</td>
<td>Intake and URV measured daily by AMF, BW measured twice a week. Final BW taken at 98 d.</td>
<td>+</td>
<td>+/−/−</td>
<td></td>
</tr>
<tr>
<td>Welk et al. (2022)</td>
<td>Wean by age at 70d; successfully 101 HF wean by intake (targets: 200, 600, 1150 g DM/d); Successfully wean by intake (target to initiate weaning; 200 g DM/d) and age (all calves weaned at 70 d)</td>
<td>101 HF</td>
<td>Group (9)</td>
<td>12 L/d</td>
<td>Wean: 31 to 69 d. Post-wean: 70 to 84 d.</td>
<td>Starter Intake ADG Final BW URV</td>
<td>Intake and URV measured daily by AMF, BW measured weekly. Final BW taken at 84 d.</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

1BS = Brown Swiss; HF = Holstein; NR = Norwegian Red.
2CS = cross-suckling; URV = unrewarded visits at the milk feeder.
3Effects are presented for intake-based weaning with respect to age-based weaning. Effect direction: “+” indicates that the effect was interpreted as positive or desirable, “−” as negative or undesirable, and “+/−” as mixed or unclear. Studies are ordered chronologically by year.
4Results dependent on weaning age. Calves weaned by intake had fewer URV during weaning and post weaning as well as greater final BW compared with calves weaned at 48 d but similar number of URV and Final BW compared with calves weaned at 88 d.
5Calves that did not meet starter intake by a set age were forced weaned and analyzed separately as “failed” calves. In general, failed calves had reduced starter intakes and growth compared with calves weaned by age and calves successfully weaned by intake.
Health

Nine studies investigated a measurement of health (diarrhea: n = 5; respiratory illness: n = 4; mortality: n = 2) with regards to weaning methods. Five of these studies assessed weaning age (Jorgensen et al., 2017a; b; Dennis et al., 2018; Barry et al., 2020; Johnson et al., 2021), 5 studies assessed weaning duration (Jorgensen et al., 2017a; b; Dennis et al., 2018; Scoley et al., 2019; Barry et al., 2020), 2 studies assessed weaning criteria (Roth et al., 2009; Barry et al., 2020), and 2 studies assessed alternative gradual weaning methods (Parsons et al., 2020; Parsons et al., 2021). Often predictions of how calf health may be affected by weaning transition are not clearly stated. Our predictions were that later weaning ages, longer weaning durations, and weaning based on starter intake, should reduce stress around weaning and thus have a protective effect on health. However, no study found a significant effect of weaning treatment on health outcomes (see Supplementary Table S2 for summary of effects; link to be provided once the paper has been reviewed). In half of these studies, health outcomes were a secondary measure, and they often lacked the sample size to appropriately compare health outcomes between treatments. The latter half of the studies were observational study designs. At best, the evidence to date from these 9 studies suggests that weaning method may not negatively impact calf health, but studies of larger populations of calves are needed to evaluate if incidence of key calf diseases like diarrhea and respiratory illness are related to weaning method. Furthermore, milk allowance and milk composition should be considered when evaluating calf health on different weaning programs; restricted milk feeding may induce behavioral indicators of stress that could lead to immunocompetence before weaning begins (reviewed by Welk et al., 2023) but this remains to be tested.

**SUMMARY OF KEY FINDINGS AND FUTURE DIRECTIONS**

This review evaluated the available literature comparing a variety of weaning methods and their effects on behavior, performance, and health. Overall, there is a scarcity of research examining common weaning methods, including earlier versus later weaning ages, longer versus shorter weaning durations, or weaning based on intake, by water dilution, by weight, or by linear or step-down gradual milk removal methods. This in part is due to our strict study inclusion criteria, which required studies to be written in English (and thus introduces a bias to including studies from North America and Europe), calves had to receive at least 4 L/d of milk during pre-weaning, and calves had to have the same pre-weaning management before weaning treatments commenced (unless an appropriate experimental design was implemented). These criteria aimed to ensure valid comparisons between weaning treatments (i.e., not confounded by differences in other management), and relevant to current calf rearing practices (i.e., feeding at least 4 L/d of milk). This review focused on outcome measures of behavior, growth, feed intake, and health; other measures, such as rumen development, are also important in evaluating the success of weaning programs but were out of the scope of this review. Our review of the 44 studies and their range of weaning methods revealed several key themes and knowledge gaps that we discuss below.

Feed intake and growth

Overall, the evidence generally suggests positive effects, or at least no negative effects, on overall growth of calves weaned at later ages, over longer durations, based on starter intake, or weaned using other gradual techniques (step-down or meal-based). This is despite delayed or overall reduced starter intakes in calves weaned at later ages; however, the majority of studies found improved starter intakes in calves weaned over longer durations. Typically, if any negative effects on growth were identified, it was during the weaning period for weaning over longer durations, but these effects disappeared post-weaning. Notably, most studies of weaning duration weaned calves at or before 8 wk of age, so weaning initiation began at very early ages for calves experiencing long weaning durations. Only 3 studies attempted to disentangle the possible interactive effects of weaning age and weaning duration with no effects (but weaning ages were at most 10 d apart, and before 8.5 wk of age) (Dennis et al., 2018; Scoley et al., 2019; Wolfe et al., 2023), and no study in this review explored how age at weaning initiation may affect feed intake and growth. We encourage future research to explore combinations of weaning duration, age of weaning initiation, and age of complete milk removal, to understand how these factors affect feed intake and growth. Furthermore, the interactions of milk allowance and different weaning approaches need further attention. For instance, 3 studies found no interactions of milk allowance and weaning duration on starter intake or performance measures (Nielsen et al., 2008a; Dennis et al., 2018; Klopp et al., 2019); this is likely because certain combinations stimulate starter intake earlier, while others stimulate starter intake later, resulting in no differences in intake or growth among the weaning combinations. However, there could be implications for rumen and gastrointestinal development when receiving...
Behavior

Some studies found no difference in growth or feed intakes across the different weaning approaches, which could lead to the conclusion that weaning earlier and/or over shorter periods is an acceptable approach. However, one must also consider how weaning methods affect the behavior and satiety of calves, since different methods can be associated with hunger. Hunger is a negative subjective affective state experienced by an animal that has been below desired intake for a long period of time or is chronically undernourished (D’Eath et al., 2009). Signs of hunger often include increased feeding motivation (such as increased visits to the automated feeder; reviewed by Welk et al., 2023), activity, and abnormal oral behaviors (D’Eath et al., 2009). These negative affective states must be minimized to maintain good animal welfare during a stressful diet transition. This review revealed that only a half of the studies (20 of the 44) evaluated some measure of behavior, such as indicators of hunger (vocalizations; unrewarded visits to the milk feeder), indicators of hunger or thwarting of sucking motivation (abnormal oral behaviors: cross-sucking; non-nutritive oral sucking), and indicators of absence of welfare threats (including absence of hunger) like play behavior and/or activity. A cautious consensus of these studies is that weaning at later ages appears to reduce signs of hunger. However, it is unclear if weaning over longer durations or weaning by starter intake reduces or prolongs hunger. This conclusion is mainly based on high numbers of unrewarded visits to the milk feeder during weaning for calves weaned over longer durations or by starter intake, and the high number of unrewarded visits post-weaning for calves weaned abruptly or by a fixed age. We suggest that calves are more likely to give up visiting the feeder once milk is no longer available; thus, calves weaned over a long period, or weaned as they meet starter intake targets, would sustain visits to the feeder as they continue to receive some milk periodically over the day.

While unrewarded visits are a convenient measure that is automatically recorded by the milk feeder, it is worth exploring other indicators of hunger or frustration around weaning, especially for calves that are not fed by automated milk feeders. Vocalizations is one indicator of hunger (Thomas et al., 2001), but only 4 studies recorded these, likely because live observation is needed until valid automated measures are available. Physiological measures of hunger or stress may help us understand how calves react to different weaning methods. For instance, Wolfe et al. (2023) found that calves weaned over very short periods (3 d) had increased heart rate and respiration rate around weaning compared with calves weaned over longer periods (14 d), suggesting that abrupt or very short weaning durations may be more stressful. Future studies should combine multiple measures of affective states, such as behavioral and physiological measures, to improve our understanding of how weaning affects calves.

There was little consensus among a total of 8 studies that measured oral behaviors of calves weaned on different programs; this likely owes to the limited number of studies that measured cross-sucking or non-nutritive oral behaviors, and during a limited observation period. Abnormal oral behaviors, such as cross-sucking, arise from a motivation to suck on a teat soon after receiving a milk meal (de Passillé, 2001). Feeding calves by bucket (Loberg and Lidfors, 2001; Jensen and Budde, 2006), low milk allowances/energy intake (Jung and Lidfors, 2001, De Paula Vieira et al., 2008), and small meal sizes (Jensen et al., 2020) have been shown to increase abnormal oral behaviors in pre-weaned calves. Thus, concern regarding abnormal oral behaviors arises around weaning when milk allowances, energy intake, and meal sizes are low. The majority of studies found no effect of weaning method on non-nutritive sucking and other oral behaviors, but there was some positive support for reduced cross-sucking in the post-weaning period for calves weaned over longer durations or weaned based on intake. Weaning over longer periods or based on intake is meant to promote familiarity and uptake of solid feeds, which may have helped to reduce hunger by increasing energy intake and thus reduced sucking motivation and the risk of cross-sucking after weaning.
However, some negative effects on cross-sucking were observed during the weaning period in calves weaned over longer durations, which may be related to very low milk allowances in the latter period of weaning or over longer periods of time. Overall, there is a need for a better understanding of how different weaning methods affect oral behaviors (both nutritive and non-nutritive), which can reveal how effective the weaning method is at easing the transition from milk to solid feed by reducing hunger and the motivation to suck. However, observation of oral behaviors is time consuming, so limited observation periods are often used which may not capture the extent of abnormal oral behaviors.

To truly understand the impact of weaning methods on abnormal oral behaviors, future studies should aim to assess full 24-h periods, particularly when milk allowances are low and on the days after weaning.

Positive behavioral indicators, such as play behavior, were rarely measured and only when comparing weaning ages (Krachun et al., 2010; Eckert et al., 2015). Play occurs spontaneously and at a low level in calves especially as they age (Krachun et al., 2010), requiring 24 h continuous observation. Nonetheless, it is interesting that one study found calves played less around weaning when weaned at 7 wk compared with un-weaned calves; however, this effect was not seen in calves weaned at older ages (13 wk) (Krachun et al., 2010). Play behavior is known to reduce or extinguish when animals are experiencing stress or sub-optimal conditions (Boissy et al., 2007; Held and Stančk, 2011), suggesting that weaning early may be especially stressful. We encourage future studies of different weaning programs to include measures of play behavior to evaluate which weaning methods are the least stressful for the calf.

Measuring calves’ use of valued resources, such as a grooming brush (Zobel et al., 2017), or motivation to obtain rewards (Lecorps et al., 2020) could also be useful methodologies to assess how calves are coping with the stress, given that cows reduce their brush use when under stress (Lecorps et al., 2021; Mandel et al., 2013). Overall, there is much to be explored with regards to how play behavior or other positive welfare indicators are affected by different weaning strategies; positive behavioral indicators are crucial to understanding the affective states of calves during this stressful diet transition.

**Health**

Very few studies examined health of calves depending on different weaning methods, and rarely was health the primary objective with sufficient sample size to conduct a valid statistical comparison of treatment groups. Historically, milk feeding was viewed to impose high risks of enteric diseases; thus, it was recommended to feed calves low milk allowances and wean at an early age to reduce the overall risk of morbidity. Current state of the art points to refute this historical viewpoint; a cautious consensus of the 9 studies measuring health is that health does not appear to be impacted by weaning methods, in terms of diarrhea and respiratory illness. However, few studies with health as a primary outcome have been conducted, making it difficult to draw strong conclusions. Future work assessing the impacts of weaning on health should compare incidence of diseases over a fixed period of time (e.g., over 14 weeks) and include daily health evaluations to ensure accurate diagnosis and measurement of disease severity.

**Review Limitations and Guidance for Future Work and Reporting**

This review was strong in its systematic approach to data collection, summarizing an overview of the weaning literature that met our inclusion criteria. The limitations of this review mainly stem from the project being undertaken by one primary author, the exclusion of non-English language studies, and the exclusion of unpublished data; thus, there is a moderate risk of confirmation and reviewer bias. In addition, studies within this review often lacked details on sample size calculations, randomization and blinding of treatments, and interrater reliability on behavioral data collection. Thus, the risk of bias with respect to methodology in the included studies was high. The majority of studies within this review were conducted under experimental conditions, likely with high levels of management and calf care. This likely does not reflect the everyday management of commercial farms which may have different types of constraints including high levels of disease, low volumes of milk, or contaminated milk supplies. Thus, how different weaning methods translate to a commercial setting needs further investigation.

Within this review differences were only described if they were deemed significant by original study authors. As mentioned above the majority of studies lacked power calculations, and lack of power could have resulted in a lack of significant results. This review did not perform a meta-analysis due to too few studies for each outcome, but with additional new studies in future, a meta-analysis would be encouraged. A major difficulty in evaluating the results of the identified studies was that studies had different weaning periods (i.e., differing in calf age and period duration) and few reported mean and standard error, making direct comparisons between studies impossible. We therefore outline several recommendations for reporting guidelines for future studies on weaning methods. First, future work should...
CONCLUSION

This review revealed a general lack of studies examining the effects of weaning methods on performance, and especially on behavior, of dairy calves. Most of the 44 studies compared different weaning ages, followed by different weaning durations. Only 15 studies explored weaning by any other method, including weaning based on starter intake, weaning by step-down reduction of milk, or weaning by water dilution. A consensus of these studies is that weaning at later ages or over longer durations has positive effects on overall growth, with no studies reporting negative effects on growth, despite reduced or delayed starter intake. Positive effects (and no negative effects) on growth were also seen in calves weaned based on starter intake (versus a fixed earlier age), weaned by step-down milk reduction (versus linearly), or weaned by reducing meal size (versus reduced meal frequency). It is important to also understand how weaning methods affect the behavior and affective state of calves; weaning at later ages appears to reduce behavioral signs of hunger, but this is less clear when weaning over longer durations or by starter intake. Additional work is required to better understand the affective states of calves when weaned using different methods. The few studies that assessed cross-sucking or other abnormal oral behaviors found no effect of weaning method, but more rigorous observation is necessary during periods of low milk allowances, especially for methods that wean over longer periods. Play behaviors were rarely measured; future research should include measures of positive welfare since these are sensitive to welfare threats, such as hunger and pain, and could be valuable for identifying lower stress weaning methods. Conclusions could not be drawn regarding calf health under different weaning methods, owing to low sample sizes. Overall, there remains significant knowledge gaps in our understanding of how best to wean calves. We argue a successful transition from milk to solid feed must minimize signs of hunger while promoting high growth and feed intakes. Thus, we strongly encourage future research to include behavioral indicators of hunger and positive welfare to evaluate how weaning methods are experienced by the calf. This includes exploring different types of gradual weaning methods, and the interactions of weaning age, weaning duration, and milk allowance.

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REFERENCES


Welk et al.: The effect of weaning…
Rahimi, A., G. R. Ghorbani, F. Hashemzadeh, M. Mirzaei, H. R. Saberipour, F. Ahmadi, and M. H. Ghaffari. 2023. Impact of corn processing and weaning age on calf performance, blood metabo-


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