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Invited review: The effect of milk feeding practices on dairy calf behavior, health, and performance—A systematic review

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ABSTRACT

The aim of this systematic review was to summarize the literature assessing the effects of milk feeding practices on behavior, health, and performance on dairy calves. Peer-reviewed, published articles, written in English, directly comparing the effects of milk allowance, milk feeding methods, or milk feeding frequency on dairy calves were eligible for inclusion. Outcome measures could include sucking behavior, sucking on a teat (nutritive sucking, non-nutritive sucking on a teat), abnormal sucking behavior (non-nutritive sucking on pen fixtures, other oral behaviors, or cross-sucking), signs of hunger (vocalizations or unrewarded visits at the milk feeder), activity (lying time or locomotor play), feeding behavior (milk intake, starter intake, milk meal duration, or starter meal duration), growth (body weight or average daily gain), and health (occurrence of diarrhea, respiratory disease, or mortality). We conducted 2 targeted searches using Web of Science and PubMed to identify key literature. The resulting articles underwent a 2-step screening process. This process resulted in a final sample of 94 studies. The majority of studies investigated milk allowance (n = 69). Feeding higher milk allowances had a positive or desirable effect on growth, reduced signs of hunger, and increased locomotor play behavior during the preweaning period, whereas starter intake was reduced. Studies addressing health pointed to no effect of milk allowance, with no consistent evidence indicating that higher milk allowances result in diarrhea. Studies addressing milk feeding methods (n = 14) found that feeding milk by teat reduced cross-sucking and other abnormal oral behaviors. However, results on the effect of access to a dry teat were few and mixed. Milk feeding frequency (n = 14 studies) appeared to have little effect on feed intakes and growth; however, there is some evidence that calves with lower feeding frequency experience hunger. Overall, findings strongly suggest feeding higher volumes of milk using a teat; however, further work is needed to determine the optimal feeding frequency for dairy calves.
Key words: milk allowance, feeding method, feeding frequency

INTRODUCTION

Early life management is fundamental to a dairy calf's welfare, performance, and lifetime productivity. For instance, previous research has shown the importance of social contact for the development of social and cognitive skills (reviewed by Costa et al., 2016; Jensen, 2018). Previous research has also highlighted the influence of preweaning ADG on the onset of puberty, age at first calving, and performance in first lactation (Raeth-Knight et al., 2009; Heinrichs and Heinrichs, 2011; Soberon et al., 2012). Enabling calves to reach their potential for growth not only includes provision of adequate nutrition to calves, but also proactive management that minimizes disease and promotes natural feeding behaviors.

Over the last 2 decades, extensive research has challenged the common practices of restricted milk feeding via a bucket. Feeding calves daily milk allowances at or above the equivalent of 20% of BW improves ADG during the preweaning period (Jasper and Weary, 2002; Miller-Cushon et al., 2013; Rosenberger et al., 2017), and feeding milk via a teat promotes natural sucking behavior and reduces abnormal oral behaviors such as sucking on pen fixtures (Appleby et al., 2001; Jensen and Budde, 2006). However, there remains debate regarding which management practices improve performance and welfare in milk-fed calves. Concerns of feeding high milk allowances arise around weaning as feeding high milk allowances reduces starter intake and slows rumen development, resulting in reduced growth and increased signs of hunger around weaning (Sweeney et al., 2010; Steele et al., 2017; van Niekerk et al., 2021).

There is large variation in milk feeding practices on dairy farms. In Norway, the average milk allowance fed

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to 3-wk-old calves was 7 L/d (range: 2 to 15 L/d), with 61% of farms feeding less than the industry recommendation of 8 L/d (Johnsen et al., 2021b). Similar preweaning milk allowances were found in the Czech Republic (6 L/d; Staněk et al., 2014) and Canada (8 L/d; Windeyer et al., 2014). However, a high percentage of farmers still report feeding calves 4 L/d in the United Kingdom (31%; Mahendran et al., 2022), United States (53%; Urie et al., 2018), and Austria (96%; Klein-Jöbstl et al., 2014). Variation in milk feeding method has also been reported, with 64% of Holstein farms in Czech Republic feeding calves by bucket (Staněk et al., 2014), 53% in the United States (Urie et al., 2018), 33% in Canada (Windeyer et al., 2014), 23% in the United Kingdom (Mahendran et al., 2022), and only 2% in Austria (Klein-Jöbstl et al., 2014). This large variability in farm milk feeding practices and continual high rates of mortality in preweaning calves reported in the industry [3.3 to 5.3% in Norway (Gulliksen et al., 2009), Canada (Windeyer et al., 2014), Switzerland (Bleul, 2011), United States (Urie et al., 2018), and the Netherlands (Santman-Berends et al., 2019)] indicate that there is still room for improvement in management on dairy farms, including improvement in milk feeding practices.

The aim of this systematic review was to summarize and identify knowledge gaps in the available literature on the effects of milk feeding practices (quantity, method, and frequency) on behavior, especially sucking behavior, performance (including feed intake and growth), and health of dairy calves. It is expected that feeding calves a higher milk allowance will improve growth and reduce behavioral signs of hunger preweaning. We also expect that feeding milk via a teat compared with a bucket or providing access to a dry teat will reduce cross-sucking and other abnormal oral behaviors while meeting the behavioral need to suck. Finally, it is expected that once-daily milk feeding does not allow young calves to meet their nutritional needs.

MATERIALS AND METHODS

Protocol and Registration

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 articles that presented primary research with either an experimental or observational study design were included in this review. 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 investigating cow-calf rearing systems were excluded. Studies were also excluded if milk allowance was <4 L/d (<3 L/d for small breeds; i.e., Jersey) in the first 21 d of life. This criterion was chosen because a milk allowance of <4 L/d does not meet dairy breeds' nutrient requirements for growth (Drackley, 2008), and young calves are unable to compensate for the energy loss from restricted milk allowances through sufficient increase in concentrate intake (Diaz et al., 2001).

Intervention Groups. Articles had to include 2 or more treatment groups that addressed one or more of the following 3 topics: milk allowance, milk feeding method, and milk feeding frequency. Milk allowance was defined as the peak amount of milk offered per day during the preweaning period. To standardize milk allowance across studies, we report all milk allowances in liters per day (L/d). Therefore, for studies to be eligible, milk allowance had to be reported in liters per day, or relevant information had to be provided to convert milk allowance to liters per day (i.e., mixing rate of milk replacer). Studies that compared different peak milk allowances but where total milk volume was similar during preweaning were excluded from this review. Studies that only reported milk allowance as total solids were also excluded. Milk feeding method was considered the method used to provide calves milk (e.g., bucket, teat) and to provide sucking opportunity (e.g., milk teat, dry teat) and could include manual or automated feeding methods. Milk feeding frequency was defined as the number of milk portions calves were offered each day during the preweaning period. Articles could also include 2 or more treatment groups that address 1 or more of the following 3 topics on weaning practices: weaning age, weaning duration, and weaning method. Results on weaning practices will be presented in a companion review.

Outcome Measures. Studies also had to include one or more outcome measures related to behavior, feed intake and growth, or health. For behavior, 5 specific sucking behaviors were defined: nutritive sucking on teat, non-nutritive sucking on teat, non-nutritive sucking on pen fixtures, other oral behaviors, and cross-sucking. Nutritive and non-nutritive sucking on a teat provide an outlet for calves' motivation to suck in relation to milk intake (de Passillé and Rushen 1997), and increases in these measures are generally evaluated as desirable and positive for animal welfare

Table 1. Description and abbreviation of sucking behaviors

Sucking behavior	Description	Abbreviation
Nutritive sucking on a teat	Sucking on milk teat and ingesting milk	NTeat
Non-nutritive sucking on a teat	Sucking on milk teat or a dry teat and no milk is ingested	NNTeat
Non-nutritive sucking on pen fixtures	Sucking on pen fixtures including bars, rim of bucket, and so on	NNPen
Other oral behaviors	Biting, licking, nibbling pen fixtures, or holding objects in the mouth	OtherOral
Cross-sucking	Sucking on any body part of another calf	CS

(for exceptions, see below). Non-nutritive sucking on pen fixtures, other oral behaviors, and cross-sucking are redirected oral behaviors due to the lack of appropriate outlet for calves' motivation to suck and are regarded as abnormal (Jensen, 2003). Increases in these abnormal oral behaviors are evaluated as negative and undesired. In certain cases non-nutritive sucking on a teat is interpreted as neutral or undesired. First, non-nutritive sucking is stimulated every time the calf ingests milk, irrespective of portion size (Rushen and de Passillé, 1995); therefore, increased non-nutritive sucking on a teat caused by allocating a given milk allowance in more milk portions is interpreted as neutral. Second, non-nutritive sucking may also be a sign of hunger (de Passillé and Rushen, 1997; Herskin et al., 2010) and, in relation to milk allowance, increased non-nutritive sucking is evaluated as negative. Detailed descriptions of these behaviors are given in Table 1. In addition, 2 measures of activity (both evaluated as desirable) and 2 measures of hunger (both evaluated as undesirable) were included: locomotor play behavior, lying time, 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 milk intake, starter intake, milk meal duration, starter meal duration, BW, or ADG (higher values being evaluated as desirable). For studies related to health, outcome measures could include mortality rate, diarrhea, and respiratory illness. These outcomes were chosen based on their frequent use in the literature, as well as their acceptability as undesirable and relating to poor animal welfare in dairy calf research.

Literature Search

Literature searches were conducted in the database of Web of Science and PubMed on March 30, 2022, and again on August 23, 2022, with no restrictions on the date of publication. Table 2 outlines the search terms used for the population, milk feeding and weaning interventions, and outcome measures. Search results were uploaded to EndNoteX7 (Clarivate Analytics). Twelve relevant studies were preselected by M. B. Jensen, and search results were checked to ensure that these studies were included. A research librarian with Aarhus University was consulted on the search strategy.

Screening Process

Studies were exported from EndNoteX7 into Covidence (Veritas Health Innovation). 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?

Table 2. Search terms used in Web of Science and PubMed searches

Area	Search term
Population	calf or calves or heifer* (title) not cow* or beef or buffalo or deer or camel (topic)
Milk feeding interventions	milk feeding or milk allowance* or milk volume* or milk feeding level or amounts of milk or milk quantity or ad libitum milk or restricted or feeding method or feeding methods or teat* or bucket or nipple or meal frequency or number of meal* or milk portion* (topic)
Weaning interventions	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)
Outcome measures	hunger or sucking or non-nutritive sucking or oral behavior* or oral behavior* or abnormal behavior* or abnormal behavior* or cross-sucking or unrewarded visit* or vocalization* or vocalizing or play behavior* or play behaviour* or feeding behavior* or feeding behaviour* or feed intake* or solid feed intake or growth or body weight or ADG or weight gain or morbidity rate* or mortality rate* or calf health or calf disease* or diarrhea or respiratory disease (topic)

(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, 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 measure: 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, or unrewarded visits at the milk feeder), feed intake and growth (milk intake, starter intake, milk meal duration, starter meal duration, BW or ADG), and health (mortality rate, incidences of diarrhea, incidences of respiratory disease, or treatment rate)?
(2) Is the milk allowance during the first 21 d of age of life ≥4 L/d?
(3) Is milk allowance reported in liters/day? If not, is all relevant information provided to convert milk allowance to liters/day?

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 N. D. Otten on the first 100 studies identified by the initial search in Web of Science. The second round of screening was pilot tested independently by A. Welk and M. B. Jensen on 48 of the 100 studies that passed the pilot test for the first round of screening.

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 feeding, milk allowance, milk type, feeding frequency, milk feeding method, starter and forage type, weaning age, weaning duration, and weaning method. Within Excel (Microsoft Corp.) using a standardized spreadsheet, detailed descriptions of treatments, outcome measures, methodology, and conclusions were extracted from each paper. Results were tabulated for each of the preweaning, weaning, postweaning, and overall experimental periods, based on the authors' classification in each study. In general, preweaning was considered when calves were receiving milk. However, when authors differentiated between the preweaning and weaning (from when milk allowance began to be reduced until milk was fully removed) periods, we reported results for the 2 periods separately. All authors considered postweaning when milk was fully removed. 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 $P \leq 0.05$. When possible, mean and standard error (SE) values of each treatment group were extracted. We present conclusions as described by the authors and the reported direction of the statistically significant effect, with "+" indicating the effect was interpreted as positive or desirable, "=" as no effect or neutral effect, and "−" as a negative or undesirable effect.

RESULTS

Search and Screening Results

The initial searches generated 1,106 unique articles, 94 of which met our inclusion criteria for milk feeding practices. Results of the search strategy and study selection are presented in Figure 1.

The final studies included in the systematic review were published between 1976 and 2022. The studies originated from 5 continents and 21 countries, most commonly Europe (n = 41: Denmark = 10, Ireland = 5, Germany = 8, Spain = 3, Sweden = 2, United Kingdom = 4, Finland = 2, Netherlands = 3, France = 2, Norway = 1, Czech Republic = 1) and North America (n = 37: United States = 19; Canada = 18). Additionally, 11 studies originated from Asia (Iran = 8, Israel = 1, Japan = 1, South Korea = 1), 3 studies from Oceania (Australia = 1, New Zealand = 2), and 2 studies from South America (Brazil = 1, Chile = 1).

Milk Allowance

A total of 69 studies investigated milk allowance, with 26 studies measuring behavior, 56 studies measuring feed intake and growth, and 30 measuring health. The majority of studies (n = 60) used an experimental study design with low milk allowance (controls) ranging from 4 to 4.9 L/d (n = 36), 5 to 5.9 L/d (n = 12), 6 to 6.9 L/d (n = 11), and 7 L/d (n = 1). Maximum milk allowance was more variable, with 15 studies assessing ad libitum milk, 7 studies assessing ≥12 L/d, 15 studies 9 to 10.9 L/d, 14 studies 8 to 8.9 L/d, and 9

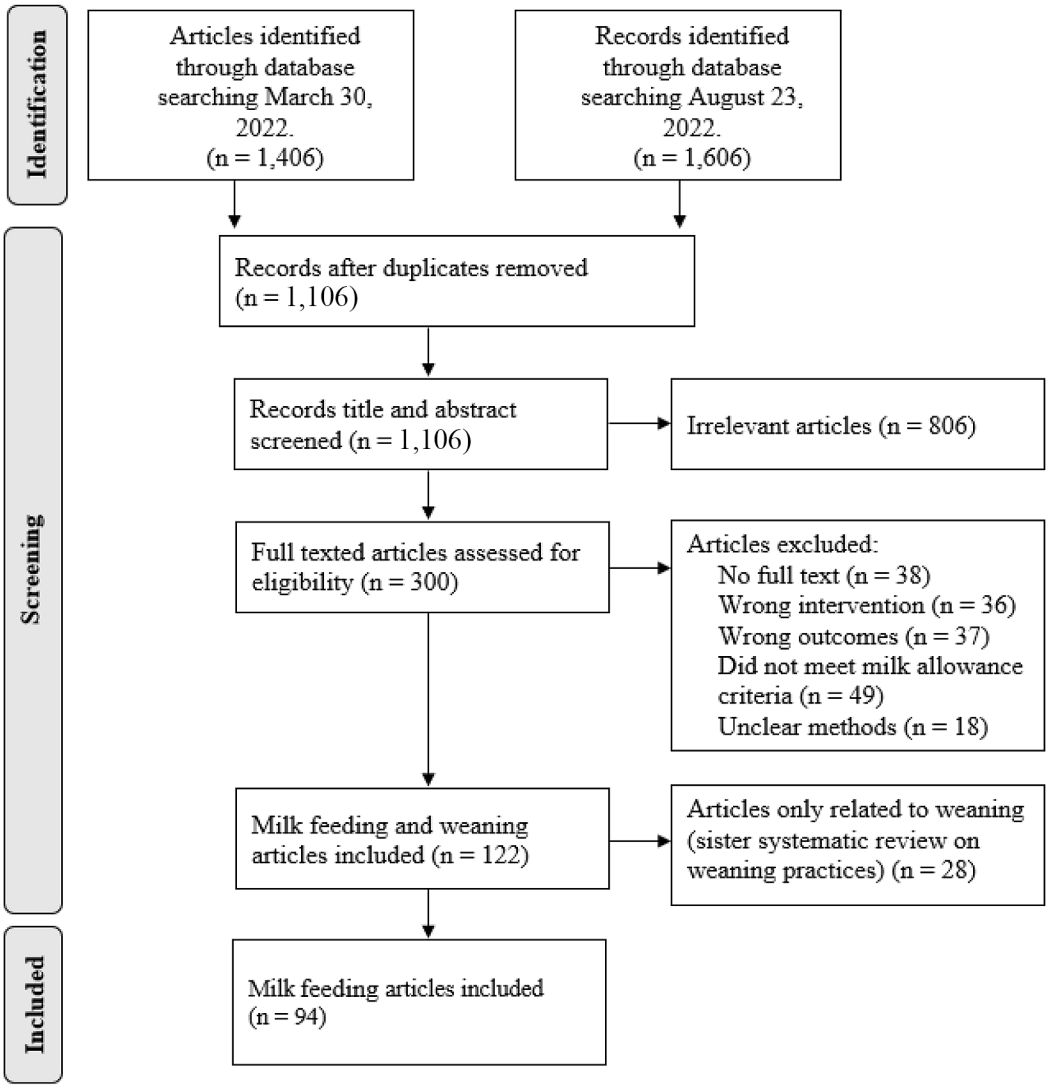

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) study flow diagram (Moher et al., 2015).

studies assessing 6 to 7.9 L/d. The remaining 9 studies consisted of 6 cross-sectional studies, 2 cohort studies, and 1 case-control study with varying milk allowances across farms.

Behavior. A total of 10 studies measured sucking behaviors (references and results presented in Table 3). Cross-sucking was measured in 5 studies, with no effect of milk allowances. Non-nutritive sucking directed at pen fixtures or other oral behaviors were measured in 4 studies, with no effect of milk allowances evident. Non-nutritive sucking directed at the milk teat or a dry teat was measured in 5 studies, with 3 studies indicating that calves fed high milk allowances spent less time sucking the milk teat after drinking a milk meal than calves fed low milk allowances.

Behaviors indicative of hunger were measured in 16 studies, with 15 studies measuring unrewarded visits at the milk feeder. Overall, calves fed higher allowances of milk engaged in fewer unrewarded visits at the milk feeder during the preweaning period (illustrated in Figure 2); 13 studies indicated a positive/desirable effect of higher milk allowances, and 2 studies found no effect. During weaning, unrewarded visits were measured in 5 studies, with 3 studies indicating a positive/desirable effect and 2 studies indicating no effect of higher milk allowances. During postweaning, unrewarded visits were measured in 5 studies, with 1 study indicating a positive/desirable effect and 4 studies indicating no effect of higher milk allowances. Vocalizations were measured in only 2 of the 16 studies. De Paula Vieira

Table 3. Studies (n = 10) investigating the effect of increasing milk allowances on sucking behavior (nutritive sucking, non-nutritive sucking on the teat, non-nutritive sucking on pen fixtures, other oral behaviors, cross-sucking) in dairy calves

Treatment	Sample size	Breed[1]	Housing (group size)	Milk feeding method	Study period (d)	Outcome[2]	Methods	Conclusions	Effect[3]	Reference[4]
4.8 L/d; 8 L/d	96	HF, DR, JER	Group (8)	Teat via automated feeder	Prewean: 15– 49 Postwean: 50–63	CS	Behavior continuously recorded (using video) for 24 h for each block of calves when the youngest was at least 21 d old and before the oldest was 49 d old.	No effect of milk allowance (median duration of CS per calf was 1.1 min/24 h).	=	Jensen and Holm, 2003
4.8 L/d; 9.2 L/d (HF and DR) 3.8 L/d; 7.2 L/d (JER)	72	HF, DR, JER	Group (12)	Teat via automated feeder	Prewean: 28–41 Wean: 42–55 Postwean: 46–61	CS	CS recorded live at 0700 to 1100 h and 1700 to 2100 h on d 41, 48, 55, 56, and 59. One-zero sampling at 30-s intervals (40 h/calf).	No effect of milk allowance.	=	Nielsen et al., 2008
						NNTeat at milk teat	NNTeat recorded by automated milk feeder as the daily duration of time a calf spent in the milk feeder after milk was fully consumed.	No effect of milk allowance preweaning. During weaning, high-milk calves spent less time NNTeat.	= (prewean)/+[5] (wean)	
4.5 L/d; ad libitum	24	HF	Group (4)	Teat via automated feeder plus access to dry teat	Prewean: 8–13	CS	Behavior continuously recorded (using video) for 24 h on d 11, 12, and 13 yielding 72 h of observations per calf.	No effect of milk allowance. CS was only reported in 3 calves.	=	De Paula Vieira et al., 2008
						NNTeat at dry teat		No effect of milk allowance. No calves sucked the dry teat.	=	
6 L/d; 12 L/d	45	HF	Group (9)	Teat via automated feeder	Prewean: 21– 49	CS	Behavior continuously recorded (using video) in six 2-h periods from 0600 to 2400 h over 2 d during wk 5 of age, yielding 24 h of observations per calf.	No effect of milk allowance. Little CS occurred, with only 4 calves CS more than 2 min/d.	=	de Passillé et al., 2011b[6]
5 L/d; ad libitum	24	HF	Individual	Teat	Prewean: 2–42	NTeat/ NNTeat at milk teat	Behavior recorded (using video) for 24 h for the first 5 d of wk 3 and wk 6. Instantaneous sampling was performed at 30-s intervals.	Calves fed ad libitum had fewer sucking bouts in wk 3, but more sucking bouts in wk 6. Sucking bout duration was lower in calves fed ad libitum wk 3 and wk 6. Calves fed 5 L/d spent considerable time sucking on the milk teat when milk was finished and during times of the day when milk was not provided.	+[5]	Miller-Cushon et al., 2013[7]
6 L/d; ad libitum	16	HF	Individual	Teat plus access to dry teat	Prewean: 1–6	NNpen/ OtherOral	Behavior continuously recorded (using video) for 24 h on d 1, 2, and 6, yielding 72 h of observation per calf.	No effect of milk allowance.	=	Todd et al., 2018[7]
						NTeat/ NNTeat at milk teat		No effect of milk allowance.	=	
						NNTeat at dry teat		No effect of milk allowance.	=	

Continued

Table 3 (Continued). Studies (n = 10) investigating the effect of increasing milk allowances on sucking behavior (nutritive sucking, non-nutritive sucking on the teat, non-nutritive sucking on pen fixtures, other oral behaviors, cross-sucking) in dairy calves

Treatment	Sample size	Breed[1]	Housing (group size)	Milk feeding method	Study period (d)	Outcome[2]	Methods	Conclusions	Effect[3]	Reference[4]
4 L/d step-down; 8 L/d step-up, step-down	60	HF	Individual	Bucket	Prewean: 1–56 Postwean: 57–70	OtherOral	Behavior was recorded live on d 40 and 47 (preweaning) for 1 h after offering fresh solid feed (1500 to 1600 h) and 2 h after evening milk feeding (1600 to 1800 h). Postweaning (d 61 and 68), behavior was recorded for 3 h after offering fresh solid feed (1500 to 1800 h). This yielded a total of 6 h of observation per calf pre- and postweaning.	No effect of milk allowance.	=	Hosseini et al., 2019
4.4 L/d; 8.8 L/d	46	HF	Individual	Teat	Prewean: 3–8	NNteat at milk teat	Behavior continuously recorded (using video) for 24 h on 3, 5, and 7 d yielding 72 h of observation per calf.	Calves fed 8.8 L/d had fewer sucking bouts and shorter sucking duration around milk feeding compared with calves fed 4.4 L/d.	+[5]	Jongman et al., 2020[8]
5 L/d; 8 L/d	48	HF	Individual	Bucket	Prewean: 4–83 Postwean: 84–103	OtherOral	Behavior recorded for 12 h after a.m. feeding on d 69, 70, 93, and 94. Five-minute interval scan sampling, yielding 48 h of observations per calf.	No effect of milk allowance.	=	Shiasi Sardoabi et al., 2021
7 to 8 L/d; 10 to 12 L/d	111 (10 farms)	HF, HF × SR, HF × FL, FL	Group (3 to 8)	Teat (8 farms); Bucket (2 farms)	Prewean: 1–70 Wean: 71–91 Postwean: 92–112	CS OtherOral	Behavior recorded (using video) for 16 h from 0600 to 2200 h for 1 d during wk 3, 7, 11, and 15. Intermittent continuous recording was used with 5-min observations taking place every 15 min; yielding 6 h 20 min of observations per calf.	No effect of milk allowance. No effect of milk allowance.	= =	Ivemeyer et al., 2022

[1]HF = Holstein-Friesian; DR = Danish Red; JER = Jersey; SR = Swedish Red; FL = Fleckvieh.

[2]See Table 1 for descriptions of abbreviations. "/" between 2 terms indicate authors grouped these behaviors into one category.

[3]Effects are presented for increasing milk allowance from a low milk allowance. Effect direction: "+" indicates that the effect was interpreted as positive or desirable, "=" indicates no effect or a neutral effect, and "−" indicates a negative or undesirable effect.

[4]Studies are ordered chronologically by year.

[5]Effect indicating a decrease in hunger in calves fed higher allowances of milk.

[6]Additional weaning age treatment; results only presented for the preweaning period.

[7]Acidified milk replacer.

[8]Additional treatment assessing feeding frequency. Results are presented in Table 8.

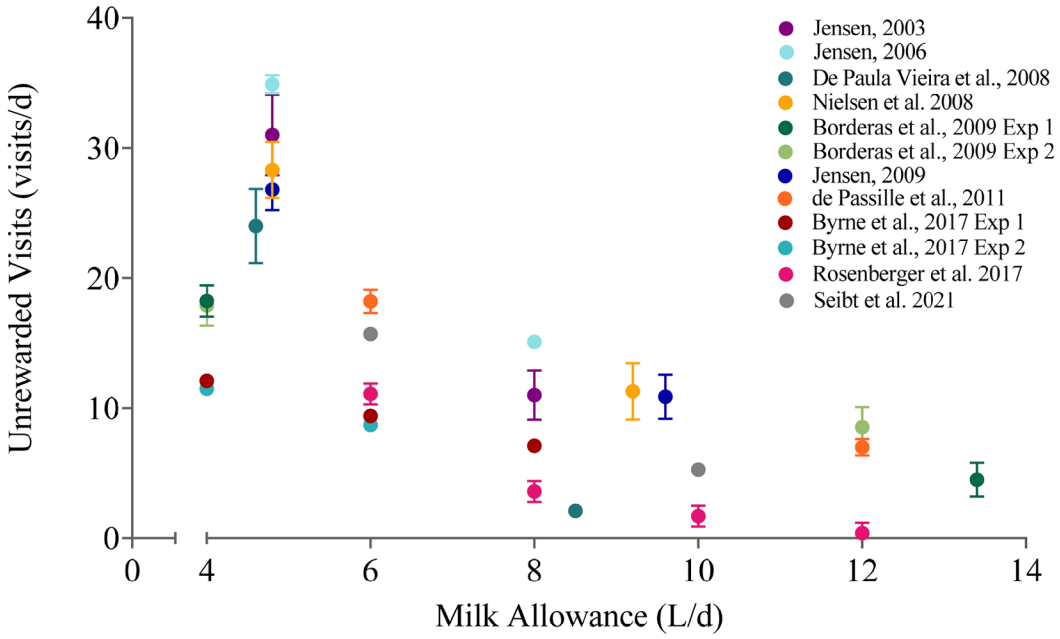

Figure 2. Relationship between milk allowance and unrewarded visits at the milk feeder during the preweaning period. The figure includes 12 out of 15 studies that provided mean (±SE) number of unrewarded visits over the preweaning period [Jensen, 2003; Jensen, 2006; De Paula Vieira et al., 2008; Borderas et al., 2009 (experiments 1 and 2); Jensen, 2009; de Passillé et al., 2011b; Byrne et al., 2017 (experiments 1 and 2); Rosenberger et al., 2017; Seibt et al., 2021].

et al. (2008) found no effect of milk allowance when offering 4.5 L/d versus ad libitum milk from 8 to 13 d of age (vocalizations recorded continuously for 48 h on d 12 to 13 of age). Postweaning, Ivemeyer et al. (2022) found that calves that had been fed higher milk allowances (10 to 12 L/d) vocalized more often than calves that had been fed low milk (7 to 8 L/d) (calves were weaned at 92 d of age and vocalizations were recorded continuously for 16 h on d 106 of age).

A total of 4 and 8 studies measured locomotor play and lying time, respectively. All studies measuring locomotor play indicated a positive (desirable) effect during the preweaning period, with calves fed higher allowances of milk engaging in more locomotor play than calves fed low milk allowances (references and results presented in Table 4). No study measured locomotor play during weaning or postweaning. In terms of lying time, 6 studies indicated no effect of milk allowance on lying time during the preweaning period, whereas 2 studies indicated a positive (desirable) effect where calves spent more time lying with increasing milk allowances (see Table 4). Two studies measured lying time postweaning with no effect of milk allowance.

Feed Intake and Growth. The studies finding positive, negative, or no effect of milk allowance on starter feed intake and growth outcomes are summarized in Table 5. Starter intake was measured in 47 studies (references and results presented in Supplemental Table S1; https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023). Thirty-seven studies reported starter intake during the preweaning period, with 15 of 37 studies reporting starter intake during weaning and 23 of 37 reporting starter intake during postweaning. The majority of studies (76%) indicated a negative or undesirable effect of higher milk allowance on preweaning starter intake, where calves fed increasing milk allowances consistently consumed less starter during the preweaning period than calves fed low milk allowances (illustrated in Figure 3). Similarly, during weaning, 67% of studies indicated a negative or undesirable effect of increasing milk allowance on starter intake. Postweaning, only 26% of studies found a negative or undesirable effect of increasing milk allowance on starter intake. Nine out of 47 studies only presented results over the experimental period, with all but 1 study indicating a negative or undesirable effect of increasing milk allowance on overall starter intake.

Starter meal duration followed a similar trend to starter intake, with 88% of studies measuring starter meal duration preweaning, and 100% of studies during weaning, all reporting a negative or undesirable effect of increasing milk allowance [Jensen, 2006; Borderas et al., 2009, experiment 1, experiment 2; Miller-Cushon et al., 2013; Hosseini et al., 2019; Sardoabi et al., 2021;

Table 4. Studies investigating the effect of increasing milk allowances on locomotor play (n = 4) and lying time (n = 8) in dairy calves

Treatment	Sample size	Breed[1]	Housing (group size)	Space allowance (m^2/calf)	Milk feeding method	Study period (d of age)	Outcome	Methods	Conclusions	Effect[2]	Reference
4.8 L/d; 8 L/d (HF and DR)	96	HF, DR, JER	Group (8)	2.5	Teat via automated feeder	Prewean: 15–49 Postwean: 50–63	Lying time	Behavior was continuously recorded (using video) for 24 h for each block of calves when the youngest was at least 21 d old and before the oldest was 49 d old.	No effect of milk allowance. (Mean lying time per calf was 16.9 h/ 24 h.)	=	Jensen and Holm, 2003
4.5 L/d; ad libitum	46	HF	Group (4)	1.8	Teat via automated feeder plus access to dry teat	Prewean: 8–13	Lying time	Behavior was continuously recorded (using video) for 24 h on d 11, 12, and 13 of age, yielding 72 h of observations per calf.	Ad libitum-fed calves spent 1 h longer lying/d compared with calves fed 4.5 L/d (17.6 vs. 18.5 h/d).	+	De Paula Vieira et al., 2008
6 L/d; 12 L/d	51	HF	Group (9)	3.7	Teat via automated feeder	Prewean: 5–49 Postwean: 50–91	Locomotor play	Behavior was continuously recorded (using video) from 0800 h to 2300 h for 2 d on 3, 5, 7, 9, 11, and 13 wk of age, yielding a total of 60 h of observations for each calf.	For all treatments, play behavior decreased with age. At 3 wk, calved fed 12 L/d had greater play duration than calves fed 6 L/d. This difference was not seen at 5 wk or postweaning (wk 7, 9, 11, and 13).	+	Krachun et al., 2010[3]
5 L/d; 9 L/d step-down[4]	48	HF	Individual; pair	13.5 (individual); 6.75 (pair)	Teat	Prewean: 1–44	Locomotor play	Behavior was continuously recorded (using video) for 48 h when the youngest calf in the block was 15, 29, and 43 d old.	On d 15, duration of play behavior was greater in calves fed 9 L/d than in calves fed 5 L/d. No differences in play behavior on d 29 or d 43 when milk allowances were similar.	+	Jensen et al., 2015[5]
6 L/d; ad libitum	16	HF	Individual	2.2	Teat plus access to dry teat	Prewean: 1–6	Lying time	Behavior was continuously recorded (using video) for 24 h starting at 1300 h on d 1, 2, and 6 of age, yielding a total of 72 h of observation per calf.	No effect of milk allowance.	=	Todd et al., 2018
4 L/d step-down; 8 L/d step-up, step-down	60	HF	Individual	3.0	Bucket	Prewean: 1–56 Postwean: 57–70	Lying time	Behavior was recorded by direct observation on d 40 and 47 (preweaning) for 1 h after offering fresh solid feed (1500 to 1600 h) and 2 h after evening milk feeding (1600 to 1800 h). Postweaning (d 61 and 68), behavior was recorded for 3 h after offering fresh solid feed (1500 to 1800 h). This yielded a total of 6 h of observation for each calf pre- and postweaning.	No effect of milk allowance.	=	Hosseini et al., 2019

Continued

Table 4 (Continued). Studies investigating the effect of increasing milk allowances on locomotor play (n = 4) and lying time (n = 8) in dairy calves

Treatment	Sample size	Breed[1]	Housing (group size)	Space allowance (m^2/calf)	Milk feeding method	Study period (d of age)	Outcome	Methods	Conclusions	Effect[2]	Reference
4 L/d; 9 L/d	74	HF	Individual	1.8	Teat	Experimental period: 5–84	Lying time	Behavior was continuously recoded for 24 h/d over the preweaning period using accelerometers.	No effect of milk allowance.	=	Scoley et al., 2019
4.4 L/d; 8.8 L/d	46	HF	Individual	11.4	Teat	Prewean: 3–8	Locomotor play	Behavior was continuously recorded (using video) for 24 h on d 3, 5, and 7 of age, yielding a total of 72 h of observation per calf.	On d 7, locomotor play was higher in calves fed 8.8 L/d in 2 portions/d than in calves fed 4.4 L/d in 1 portion/d. Calves fed 4.4 L/d in 2 portions/d had intermediate levels of locomotor play.	+ (dependent on feeding frequency)	Jongman et al., 2020[6]
							Lying time		No effect of milk allowance.	=	
6 L/d; 12 L/d	72	HF	Group (3)	2.0	Teat	Prewean: 13–56	Locomotor play	Locomotor play was measured using accelerometer over 2 consecutive days from 0500 to 2300 h during 4 and 8 wk of age yielding a total of 72 h of observations per calf.	Calves fed 12 L/d in stable groups had greater play duration and bout frequency at 4 and 8 wk compared with calves fed 12 L/d in mixed groups, and calves fed 6 L/d in both stable and mixed groups.	+ (dependent on regrouping)	Größbacher et al., 2020[7]
5 L L/d; 8 L/d	48	HF	Individual	3.2	Bucket	Prewean: 4–83 Postwean: 84–103	Lying time	Behavior was recorded by direct observation using instantaneous recording at 5-min interval for 12 h after a.m. feeding on d 69, 70, 93, and 94 of age yielding 48 h of observations per calf.	No effect of milk allowance pre- or postweaning. However, calves fed 5 L/d tended to spend less time lying than calves fed 8 L/d preweaning (374.2 vs. 352.4 min).	=	Shiasi Sardoabi et al., 2021
5 L/d; 10 L/d	50	HF, JER, HF × JER, HF × Hereford	Group (4 to 8)	4.5 to 2.2	Teat via automated feeder	Prewean: 4–28	Lying time	Behavior was continuously recoded for 24 h/d over the preweaning period using accelerometers.	Calves fed 10 L/d spent more time lying than calves fed 5 L/d. Mean lying time was 17.4 h/d (range: 16.5 h to 19.8 h/d) in calves fed 10 L/d, and calves fed 5 L/d spent 17.1 h/d lying (range: 15.5 to 19.8 h/d) .	+	Lowe et al., 2022[8]

[1]HF = Holstein-Friesian; DR = Danish Red; JER = Jersey.

[2]Effects are presented for increasing milk allowance with respect to low milk allowance. Effect direction: "+" indicates that the effect was interpreted as positive or desirable and "−" as negative or undesirable. Studies are ordered chronologically by year.

[3]Additional weaning age treatment; results only presented for the preweaning period.

[4]Calves fed 9 L/d had milk reduced to 5 L/d on d 29.

[5]Additional treatment assessing regrouping and the effect on play behavior.

[6]Additional treatment assessing feeding frequency. Results are presented in Supplemental Table S5 (https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023).

[7]Additional housing treatment assessing individual versus pair housing.

[8]Additional treatment assessing water access.

Table 5. Number of studies finding a positive or desirable (+), neutral (=), or negative or undesirable (–) effect of increasing milk allowances on starter intake, starter meal duration, ADG, and BW during preweaning, weaning, postweaning, or over the experimental period

Variable	No. of studies[1]	Preweaning			Weaning			Postweaning			Experimental period		
		+	=	–	+	=	–	+	=	–	+	=	–
Starter intake	47	2	7	30	1	4	10	2	15	6	1	0	7
Starter meal duration	8	0	1	7	0	0	3	1	1	4	0	0	0
ADG	51	37	4	0	2	7	6	4	16	4	9	1	0
BW	43	28	5	0	5	4	0	12	9	0	7	3	0

[1]References and results presented in Supplemental Table S1 (https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023).

Ivemeyer et al., 2022; Lowe et al., 2022]. Postweaning, a majority of studies (67%) reported no effect of milk allowance on starter meal duration.

A total of 56 studies measured growth, with 51 reporting ADG and 43 reporting BW (references and results reported in Supplemental Table S2; https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023). Overall, 41 studies reported ADG during the preweaning period, with 15 of 41 studies reporting ADG during weaning and 24 of 41 reporting ADG postweaning. The majority of studies (90%) reported a positive or desirable effect of increasing milk allowance on ADG during the preweaning period, with calves fed higher milk allowances having greater ADG than calves fed low milk allowances (illustrated in Figure 4). During weaning, only 15% of studies indicated a positive or desirable effect of higher milk allowances on ADG; during postweaning, the majority of studies (67%) indicated no effect of milk allowance on ADG. Ten studies reported ADG over the experimental period, with 9 studies finding a positive or desirable effect of higher milk allowances on ADG. In terms of BW, 33 studies reported BW during the preweaning period 9 of the 33 studies reported BW during weaning, and 21 of 33 reported BW postweaning. Similar to ADG, 85% of studies indicated a positive or desirable effect of increasing milk allowance on preweaning BW. During weaning, results were mixed, with 55% of studies reporting a positive or desirable effect of higher milk allowances, whereas 44% reported no effect. Postweaning, 57% of studies reported a positive or desirable effect of higher milk allowances on BW. Ten studies only reported BW over the experimental period, with 7 studies reporting a positive or desirable effect of higher milk allowances

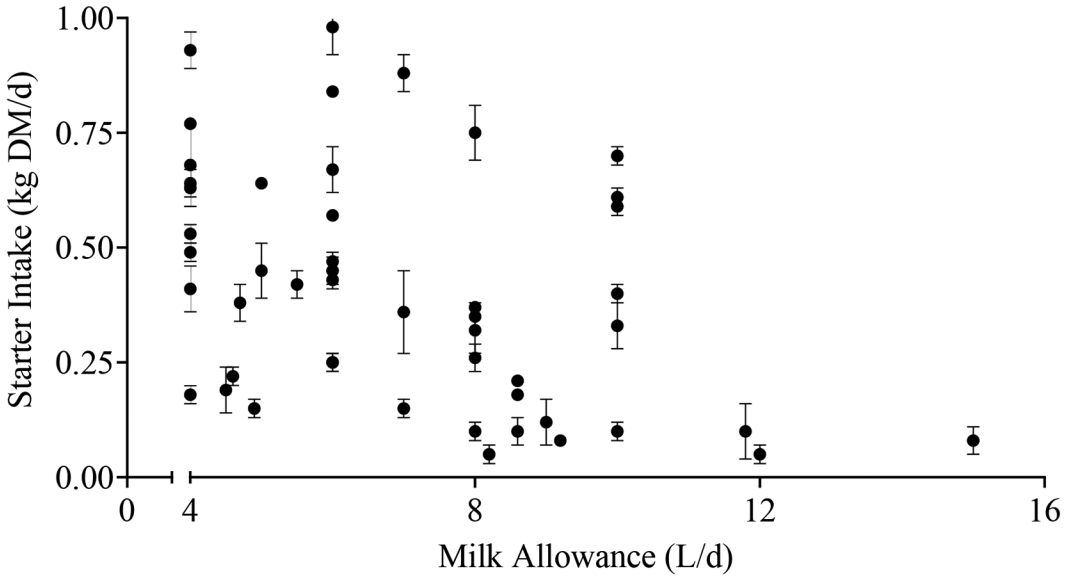

Figure 3. Relationship between starter intake and milk allowance during the preweaning period. Figure includes 22 out of 38 studies that provided mean (±SE) starter intake over the preweaning period. In addition, studies must have reported starter intake as kilograms of DM per day or provided DM of starter to convert to kilograms of DM per day. Studies reporting starter intake only during the first 3 wk of life were also excluded from the figure due to low starter intake at that age [Appleby et al., 2001; Jasper and Weary, 2002; Shamay et al., 2005; Khan et al., 2007; Terré et al., 2007; Huuskonen and Khalili, 2008; Huuskonen et al., 2011; Miller-Cushon et al., 2013; Kiezebrink et al., 2015; Omidi-Mirzaei et al., 2015; Leão et al., 2016; Byrne et al., 2017 (experiments 1 and 2); Frieten et al., 2017; Korst et al., 2017; Rosenberger et al., 2017; Hosseini et al., 2019; Alimirzaei et al., 2020; Jafari et al., 2021; Suarez-Mena et al., 2021; Kazemi-Bonchenari et al., 2022; Parsons et al., 2022].

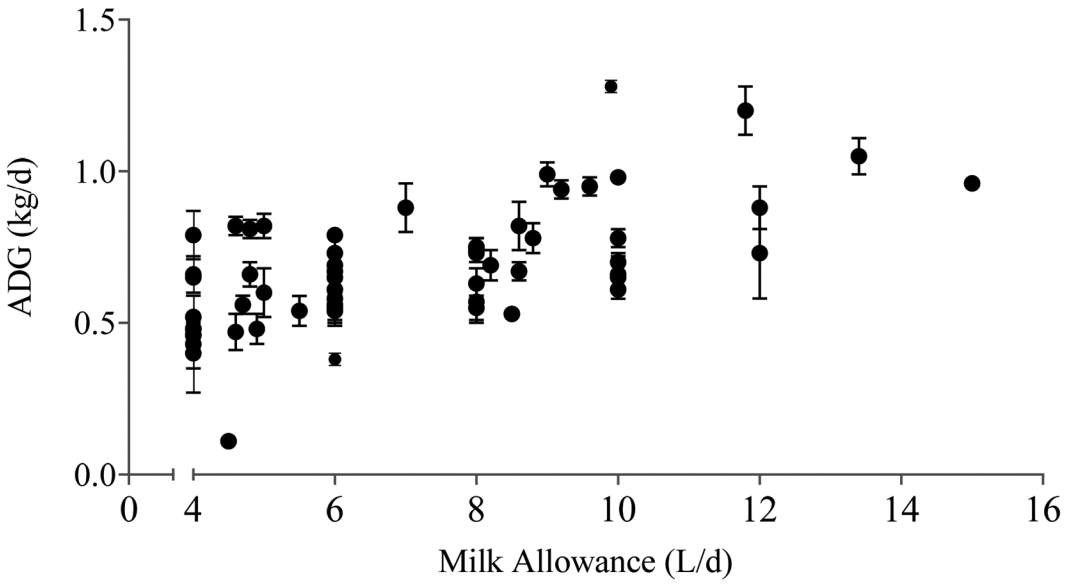

Figure 4. Relationship between ADG and milk allowance during the preweaning period. Figure includes 26 out of 41 studies that provided mean (±SE) ADG over the preweaning period [Appleby et al., 2001; Jasper and Weary, 2002; Jensen, 2006; Terré et al., 2007; Huuskonen and Khalili, 2008; Nielsen et al., 2008; De Paula Vieira et al., 2008; Borderas et al., 2009 (experiments 1 and 2); Jensen, 2009; Huuskonen et al., 2011; Miller-Cushon et al., 2013; Jensen et al., 2015; Maccari et al., 2015; Omidi-Mirzaei et al., 2015; Yunta et al., 2015; Leão et al., 2016; Byrne et al., 2017 (experiments 1 and 2); Rosenberger et al., 2017; Hosseini et al., 2019; Jafari et al., 2021; Suarez-Mena et al., 2021; Ivemeyer et al., 2022; Kazemi-Bonchenari et al., 2022; Parsons et al., 2022].

and 3 studies reporting no effect. Overall, no study reported a negative or undesirable effect of increasing milk allowance on BW.

Health. The studies finding positive, negative, or no effect of milk allowance on health outcomes are summarized in Table 6. A total of 30 studies measured health, with 25 studies measuring diarrhea, 11 measuring respiratory disease, and 5 measuring mortality rates (references and results presented in Supplemental Table S3; https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023). Overall, milk allowance had little effect on health. All studies measuring mortality reported no effect of milk allowance. Similarly, 91% studies measuring respiratory disease reported no effect of milk allowance. However, some discrepancies were found in studies assessing diarrhea, with 5 studies (19%) reporting an increase in diarrhea and 5 studies (19%) reporting a decrease in diarrhea with increased milk allowance.

Milk Feeding Method

A total of 14 studies investigated milk feeding methods, with 12 studies measuring behavior, 6 studies measuring feed intake and growth, and 5 measuring health. Nine experimental studies investigated milk feeding with a bucket versus a teat, with 2 of 9 studies incorporating a dry teat into their study design. One study investigated the use of a Braden bottle (teat bottle filled with starter). Only one study investigated no access to a dry teat versus access to a dry teat in calves feed milk by a bucket. Three experimental studies investigated manual versus automated feeding, with 2 studies manually feeding milk through a teat and one study manually feeding milk by a bucket. Finally, 1 cross-sectional observational study investigated access to a dry teat and milk feeding by a trough, bucket, or teat.

Behavior. All studies measuring behavior (n = 12) assessed sucking behaviors (references and results presented in Table 7). Cross-sucking was measured in 3 studies investigating bucket versus teat feeding, with all 3 studies reporting a positive or desirable effect of teat feeding where calves feed milk through a teat engaged

Table 6. Number of studies finding positive or desirable (+), neutral (=), or negative or undesirable (−) effect of increasing milk allowances on health over the experimental period

		Effect		
Variable	No. of studies[1]	+	=	−
Diarrhea	26	5	16	5
Respiratory disease	11	1	10	0
Mortality rate	5	0	5	0

[1]References and results presented in Supplemental Table S3 (https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023).

in less cross-sucking than calves fed milk through a bucket. Five studies comparing bucket versus teat feeding measured non-nutritive sucking on pen fixtures, and other oral behaviors were measured in 5 studies investigating bucket versus teat feeding, with 4 studies finding a positive or desirable effect of feeding milk through a teat (i.e., a decrease in non-nutritive sucking on pen fixtures and other oral behaviors) and 1 study reported no effect. All studies investigating bucket versus teat feeding indicated that teat-fed calves spent a proportion of time sucking at the milk teat after the milk meal. Two studies also noted that bucket-fed calves directed non-nutritive sucking at the milk bucket after a milk meal. In a cross-sectional study, Reipurth et al. (2020) found that calves fed milk with a teat were 20 times less likely to perform non-nutritive sucking behaviors (including cross-sucking, non-nutritive sucking at the teat and pen fixtures, and other oral behaviors) than calves fed milk in a bucket or trough.

The effect of dry teat access on sucking behavior was less clear (Table 7). Reipurth et al. (2020) found that having access to a dry teat did not affect non-nutritive sucking behaviors. Similarly, Kopp et al. (1986) found no differences in non-nutritive sucking and other oral behaviors between bucket-fed and teat-fed calves when given access to dry teats. On the other hand, Salter et al. (2021) found that bucket-fed calves with access to a Braden bottle spent less time cross-sucking than bucket-fed calves with no access to a Braden bottle; however, bucket-fed calves with access to a Braden bottle spent more time cross-sucking than teat-fed calves. Calves also appeared to favor the milk teat over a dry teat. Hammell et al. (1988) found that bucket-fed calves spent more time sucking on a dry teat than teat-fed calves offered a dry treat. Jung and Lidfors (2001) found no difference in non-nutritive teat sucking between bucket-fed and teat-fed calves both offered a dry teat, but found that teat-fed calves consistently directed non-nutritive teat sucking at the milk teat. Finally, Salter et al. (2021) found that bucket-fed calves used the Braden bottle more often than teat-fed calves. No differences in sucking behaviors were found in the 3 studies investigating manual and automated milk feeding.

Few studies investigated behaviors related to activity and hunger. Lying time was measured in 4 studies (Hammell et al., 1988; Veissier et al., 2002; Jensen and Budde, 2006; Horvath and Miller-Cushon, 2017), and locomotor play behavior was measured in 1 study (Reipurth et al., 2020) investigating bucket versus teat feeding; however, no treatment differences were evident (references and results presented in Supplemental Table S4; https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023). The 3 studies investigating manual versus automated milk feeding (Sinnott et al., 2021, 2022; Webb et al., 2015) recorded lying time and locomotor play behavior. Only 1 study indicated a negative or undesirable effect of automated milk feeding on lying time, where calves fed by automated feeders spent less time lying at 15 wk of age than calves fed manually (Webb et al., 2015). Vocalizations were measured in 1 study investigating bucket versus teat feeding, with bucket-fed calves vocalizing more than teat-fed calves when offered 4 L/d of milk over the experimental period (5 to 49 d; Kopp et al., 1986).

Feed Intake and Growth. Starter intake was measured in 2 studies (Horvath and Miller-Cushon, 2017; Sinnott et al., 2021), and starter meal duration was measured in 1 study (Horvath and Miller-Cushon, 2017). No difference in starter intake or starter meal duration was reported between bucket-fed and teat-fed calves (Horvath and Miller-Cushon, 2017); however, Sinnott et al. (2021) found that manually fed calves consumed more starter than calves fed by an automatic milk feeder (over experimental period: 14 to 160 d of age). Only 1 study measured milk intake and indicated that bucket-fed calves drank less milk than teat-fed calves (preweaning period: 1 to 37 d of age; Hammell et al., 1988). Milk meal duration was reported in 6 studies, with 1 study reporting no effect (Loberg and Lidfors, 2001), whereas 5 studies found that teat-fed calves spent more time ingesting milk than bucket-fed calves, regardless of access to a dry teat or Braden bottle (Hammell et al., 1988; Jung and Lidfors, 2001; Veissier et al., 2002; Jensen and Budde, 2006; Salter et al., 2021).

Milk feeding method had little effect on growth, with no differences between bucket versus teat feeding (Bernal-Rigoli et al., 2012; Horvath and Miller-Cushon, 2017; Deikun et al., 2020), manual versus automated feeding (Sinnott et al., 2021, 2022), or access to a dry teat (Deikun et al., 2020). Only 1 study reported a positive or desirable effect on growth: teat-fed calves with access to a dry teat had greater ADG preweaning (1 to 37 d) compared with bucket-fed calves with access to a dry teat (Hammell et al., 1988).

Health. Health outcomes were reported in 5 studies, with all 5 studies investigating diarrhea and 4 studies investigated respiratory disease (Bernal-Rigoli et al., 2012; Deikun et al., 2020; Sinnott et al., 2021, 2022). Only 2 studies reported an effect of milk feeding method on diarrhea. Bernal-Rigoli et al. (2012) found that diarrhea (based on fecal scores) among group-housed calves was higher in bucket-fed than teat-fed calves, but this effect was not seen among individually housed calves. Sinnott et al. (2021) found that manually fed calves had a greater risk of developing diarrhea than automated-fed calves (a fecal scores greater than 0). No effect of milk feeding method on respiratory disease was reported.

Table 7. Studies (n = 13) investigating the effect of milk feeding method on sucking behavior (nutritive sucking, non-nutritive sucking on the teat, non-nutritive sucking on pen fixtures, other oral behaviors, cross-sucking) in dairy calves

Treatment	Sample size	Breed[1]	Housing (group size)	Milk allowance (L/d)	Study period (d)	Outcome[2]	Methods	Conclusion	Effect[3]	Reference
Bucket vs. teat or access to a dry teat										
Bucket; Teat; Bucket with access to dry teat; Teat with access to dry teat	44	HF	Individual	4	Experimental period: 1–49	NNPen/OtherOral	Behavior was recorded twice a week during wk 1, 3, 5, and 7 at 1000 or 1400 h (between milk feedings) for 5 min after a focal object for sucking (a bicycle inner tube) was placed in the pen, yielding 40 min of observations per calf. Twice-daily milk feedings occurred at 0900 and 1700 h.	No effect of milk feeding method.	=	Kopp et al., 1986
Bucket with access to dry teat; Teat with access to dry teat	14	HF	Individual	Ad libitum	Experimental period: 17–41	NNTeat at dry teat	Behavior was continuously recorded (using video) on d 19, 21, 31, and 37 of age.	Teat-fed calves spent less time sucking the dry teat than bucket-fed calves.	+[4]	Hammell et al., 1988
Bucket with access to dry teat; Teat with access to dry teat	12	HF, SRW, HF × SRW	Individual	Ad libitum	Prewean: 28–56	NNTeat at both milk and dry teat	Behavior was recorded by direct observations using instantaneous recording at 20-s intervals for 30 min after milk was ingested during the a.m. and p.m. milk feedings.	NNTeat was similar in bucket-fed calves and teat-fed calves offered a dry teat; however, teat-fed calves directed NNTeat toward the milk teat.	+[4]	Jung and Lidfors, 2001 Exp. 2
Bucket; Teat	16	SRW	Pair	5	Prewean: 9–35	CS NNTeat at milk teat /NNPen OtherOral	Behavior was recorded by direct observation over 30 min, using instantaneous recording for 20-s intervals, after the a.m. and p.m. milk feedings when milk was fully ingested on d 7, 14, 21, and 28.	Bucket-fed calves with fast milk flow had greater rates of CS than teat-fed calves and bucket-fed calves with slow milk flow. Fast milk flow calves had greater recordings of NNTeat/ NNPen; however, bucket-fed calves directed NNteat or OtherOral at the edge and bottom of the bucket, whereas teat-fed calves directed 95% of NNTeat at the milk teat.	+ (conditional on milk flow) + (conditional on milk flow) + (conditional on milk flow)	Loberg and Lidfors 2001[5]
Bucket; Teat	24	HF	Individual	Not provided	Experimental period: 14–120	NNPen, OtherOral	At 1.5 and 2.5 mo of age, behavior was continuously recorded (using video) during 15 min before and 60 min after a.m. milk delivery. At 3 mo of age, behaviors were recorded instantaneously at 3-min intervals (using video) for 2 consecutive days for 12 h/d (0700 to 1800 h).	NNPen was only observed in bucket-fed calves, occurring for 10 min following a milk meal. Teat-fed calves spent less time performing OtherOral behaviors for 25 min following a milk meal.	+ +	Veissier et al., 2002 Exp. 1[6]

Continued

Table 7 (Continued). Studies (n = 13) investigating the effect of milk feeding method on sucking behavior (nutritive sucking, non-nutritive sucking on the teat, non-nutritive sucking on pen fixtures, other oral behaviors, cross-sucking) in dairy calves

Treatment	Sample size	Breed[1]	Housing (group size)	Milk allowance (L/d)	Study period (d)	Outcome[2]	Methods	Conclusion	Effect[3]	Reference
Bucket; Teat	96	HF	Pair; Group (6)	6	Experimental period: 17–56	CS	Behavior was recorded by direct observation during the a.m. milk feeding for 30 min (starting when milk was delivered) using instantaneous sampling at 45-s or 60-s intervals. Recorded once at 2, 4, and 6 wk of age.	Teat-fed calves spent less time CS than bucket-fed calves (0.2 ± 0.2 vs. 1.9 ± 0.6 min/30 min).	+	Jensen and Budde, 2006
						NNTeat at milk teat /NNPen		Teat-fed calves spent 5.5 ± 0.9 min/30 min sucking on the milk teat compared with bucket-fed calves, spending 0.1 ± 0.1 min/30 min sucking the bucket.	+	
						OtherOral		Teat-fed calves spent less time performing OtherOral behaviors than bucket-fed calves (0.8 ± 0.2 vs. 1.4 ± 0.2 min/30 min).	+	
Bucket; Teat	30	HF	Individual	6	Prewean: 14–42	NNPen	Behavior was continuously recorded over 2 consecutive days during 2 and 4 wk of age. Calves were observed from 0600 to 1000 h and 1600 to 2000 h during the 0600 h and 1800 h milk feeding.	No effect of milk feeding method.	=	Horvath and Miller-Cushon, 2017[7]
Trough: bucket; Teat	51 group of calves (across 27 farms)	HF, DR, JER	Group	5 to 12 (range of milk fed on farms)	Prewean: 7–70	Total non-nutritive sucking (including CS, NNTeat, NNPen, and OtherOral)	Behavior was continuously recorded using video for 30 min after the a.m. or p.m. milk feeding.	Total non-nutritive sucking was lower in teat-fed calves (0.9 min/30 min) than in trough- (4.1 min/30 min), and bucket-fed calves (3.7 min/30 min). Teat-fed calves were 20 times less likely to perform non-nutritive sucking behaviors than the reference group of trough-fed calves.	+	Reipurth et al., 2020
No dry teat; Access to dry teat								Total non-nutritive behaviors were not affected by the presence of a dry teat.	=	

Continued

Table 7 (Continued). Studies (n = 13) investigating the effect of milk feeding method on sucking behavior (nutritive sucking, non-nutritive sucking on the teat, non-nutritive sucking on pen fixtures, other oral behaviors, cross-sucking) in dairy calves

Treatment	Sample size	Breed[1]	Housing (group size)	Milk allowance (L/d)	Study period (d)	Outcome[2]	Methods	Conclusion	Effect[3]	Reference
Bucket; Teat; Bucket with access to Braden bottle; Teat with access to Braden bottle	64	HF	Pair	8	Prewean: 1–56	CS	Behavior was recorded by direct observation using continuous recording during 30 min starting at the beginning of the p.m. milk meal. Recordings were made 2 times a week from 3 to 8 wk of age, yielding 6 h of observations per calf.	Bucket-fed calves with no access to a Braden bottle spent more time CS than other treatments. In addition, bucket-fed calves with access to a Braden bottle spent more time CS before weaning than teat-fed calves (regardless of Braden bottle access).	+	Salter et al., 2021
						NNPen/OtherOral		NNPen/OtherOral behaviors were lower in teat-fed calves than in bucket-fed calves before (0.1 ± 0.07 min vs.1.2 ± 0.07) and during weaning (0.4 ± 0.1 min vs. 1.6 ± 0.1).	+	
						NNTeat at milk and Braden bottle teat		Calves fed milk through a teat consistently directed NNTeat toward the milk teat. Braden bottle use was lower in calves fed milk through a teat than a bucket.	+[4]	
Manual vs. automated milk feeding										
Manual (bucket-fed); Automated	80	HF	Group (5)	Not provided	Experimental period: 91–203	CS OtherOral	Behavior was recorded for 2 consecutive days during wk 15 and wk 24 using instantaneous sampling at 6-min intervals. Observations were done during 30 min every 2 h from 0630 to 2030 h.	No effect of milk feeding method.	= =	Webb et al., 2015[6]
Manual (teat-fed); Automated	60	HF, HF × JER	Group (15)	6	Experimental period: 3–160	CS NNTeat at milk teat /NNPen/OtherOral	Behavior was recorded once a week over the experimental period using instantaneous recording at 1-min intervals for a duration of 15 min, 5 times per day.	No effect of milk feeding method.	= =	Sinnott et al., 2021[6]
Manual (teat-fed); Automated	76	HF, HF × JER	Group (6 to 12)	8	Experimental period: 3–160	CS NNTeat at milk teat /NNPen/OtherOral	Behavior was recorded once a week over the experimental period using instantaneous recording at 1-min intervals for a duration of 15 min, 5 times per day.	No effect of milk feeding method.	= =	Sinnott et al., 2022[6]

[1]HF = Holstein-Friesian; DR = Danish Red; JER = Jersey; SRW = Swedish Red and White.

[2]See Table 1 for descriptions of abbreviations. "/" between 2 terms indicate authors grouped these behaviors into one category.

[3]Effects are presented for teat feeding or automated feeding with respect to bucket feeding or manual feeding. Effect direction: "+" indicates that the effect was interpreted as positive or desirable and "−" as negative or undesirable. Studies are ordered chronologically by year.

[4]Effect indicating that the milk teat provides an outlet for sucking motivation.[5]Additional treatment assessing milk flow.

[6]Studies assessing calves reared under a veal production system.

[7]Additional treatment assessing access to forage.

Milk Feeding Frequency

Fourteen studies investigated milk feeding frequency, with 8 measuring behavior, 12 measuring feed intakes and growth, and 3 measuring health. A total of 8 studies used manual milk feeding methods, with 5 studies investigating 1 portion/d versus 2 portions/d (i.e., a daily milk feeding frequency of 1 vs. 2), and 2 studies investigating 2 portions/d versus 3 portions/d. Last, 1 study provided calves with either 4 h of access to ad libitum milk split into 2 periods of access per day or continuous access (24 h/d). For studies using automated milk feeding, 2 studies programmed the feeders to distribute milk allowance into 4 versus 8 portions/d, whereas 1 study programmed the automated feeders to distribute milk allowance into 2 versus 4 portions/d. The fourth automated feeding study either restricted meal size so calves would receive numerous small meals per day (maximum milk meal size of 2.3 L) or unrestricted meal size so calves could have fewer large meals per day (maximum milk meal size equal to daily milk allowance). Finally, 2 studies used a cohort study design and classified milk feeding frequency as 3 meal/d by automated feeders, 2 meal/d by bucket, 1 meal/d by bucket, or continuous access to milk allowance.

Behavior. A total of 6 studies investigated sucking behavior (references and results on sucking behavior are presented in Table 8). Cross-sucking was measured in 3 studies, with no effect of milk feeding frequency reported. Non-nutritive sucking at the milk teat was measured in 4 studies, with all 4 indicating that calves with greater feeding frequencies spent more time non-nutritive sucking around milk feeding compared with calves with lower feeding frequencies. One study measured other oral behaviors defined as time spent manipulating the teat (actively pushing, butting, or biting but not sucking the teat) in the automated feeder. Results indicated that calves offered fewer but larger portions per day spent more time manipulating the teat compared with calves offered many small portions per day.

A total of 8 studies measured lying time, with 7 studies reporting no effect of feeding frequency (references and results on lying and play behavior are presented in Supplemental Table S5; https://data.mendeley.com/datasets/jgw6k9ms9s; Welk et al., 2023). One study indicated a positive or desirable effect of increased feeding frequency on lying time where calves that had access to many small portions per day had greater lying times than calves that had access to fewer but larger portions per day (Jensen et al., 2020). Only 2 studies measured locomotor play (Rasmussen et al., 2006; Jongman et al., 2020), with no effect of feeding frequency.

Two studies measured unrewarded visits to the milk feeder. One study reported no treatment effect of feeding calves (12 to 70 d of age) 6.4 L/d (4.8 L/d for small breeds) in 4 or 8 portions/d through an automated feeder (Jensen, 2004), whereas the other study indicated that calves fed 8 L/d in 2 portions/d had a greater number of unrewarded visits than calves fed the same allowance in 4 portions/d (MacPherson et al., 2019). No study measured vocalizations.

Feed Intake and Growth. A total of 7 studies measured starter intake, with 6 studies reporting no difference in starter intake (Van Horn et al., 1976; von Keyserlingk et al., 2006; MacPherson et al., 2019; Saldana et al., 2019; Grice et al., 2020; Scoley et al., 2020); 1 study investigating 2 versus 3 portions/d reported a negative or undesirable effect of increased milk feeding frequency, where calves fed 3 portions/d consumed less starter (Jafari et al., 2021). The 1 study measuring starter meal duration indicated that calves fed fewer but larger milk meals spent more time eating starter during the preweaning period (12 to 56 d of age) than calves with many smaller meals when fed by an automated feeder (Jensen et al., 2020).

Six studies measured milk intake, with 3 studies reporting a positive or desirable effect of increased feeding frequency, and 1 study reported a negative or undesirable effect. von Keyserlingk et al. (2006) found calves with 24 h of access to ad libitum milk tended to ingest 10% more milk daily than calves with only 4 h of access during the preweaning period (5 to 35 d or age). Jongman et al. (2020) found that calves offered a daily milk allowance equivalent to 10% of BW (~4.4 L/d) in 2 portions/d ingested 50% more milk at 3 d of age and 20% more milk at 4 d of age compared with calves fed the same milk allowance but in 1 portion/d. In contrast, Grice et al. (2020) found that calves fed 6.7 L/d in 2 portions/d consumed more milk than calves fed 3 portions/d (preweaning period: 3 to 42 d of age). Three studies reported no effect of feeding frequency on milk intake, all using automated feeding (Jensen, 2004; MacPherson et al., 2019; Jensen et al., 2020). One study measured milk meal duration, with no difference reported between calves (1 to 30 d of age) fed 6.4 L/d (4.8 L/d for small breeds) in 4 versus 8 portions/d when fed by an automated feeder (Rasmussen et al., 2006).

None of the 12 studies measuring growth reported an effect of milk feeding frequency, with 8 studies using manual feeding (van Horn et al., 1976; von Keyserlingk et al., 2006; Kienitz et al., 2017; Saldana et al., 2019; Grice et al., 2020; Jongman et al., 2020; Scoley et al., 2020; Jafari et al., 2021) and 4 studies using automated feeding (Jensen, 2004; Rasmussen et al., 2006; MacPherson et al., 2019; Jensen et al., 2020).

Health. None of the 3 studies measuring health found an effect of milk feeding frequency. Two studies

Table 8. Studies (n = 6) investigating the effects of increasing milk feeding frequency on sucking behavior (nutritive sucking, non-nutritive sucking on the teat, non-nutritive sucking on pen fixtures, other oral behaviors, cross-sucking) in dairy calves

Treatment	Sample size	Breed[1]	Housing (group size)	Milk allowance (L/d)	Study period (d of age)	Outcomes[2]	Methods	Conclusion	Effect[3]	Reference
Manual milk feeding										
4-h access; 24-h access	28	HF	Individual	Ad libitum	Prewean: 5–35	NTeat/NNTeat	Behavior was recorded (using video) during 48 h starting on d 32 of age using instantaneous recording at 20-s intervals.	Calves with 24-h access to milk spent more time sucking the teat than calves with 4-h access to milk split into 2 feedings.	=[4]	von Keyserlingk et al., 2006
1 portion/d; 2 portions/d	46	HF	Individual	4.4; 8.8	Prewean: 3–8	NNTeat	Behavior was recorded continuously by video for 24 h/d on d 3, 5, and 7, resulting in a total of 72 h of observation per calf.	Daily values for non-nutritive sucking at the teat was similar between calves fed 1 portion/d and 2 portions/d. However, around milk feeding, calves fed 2 portions/d had greater number of non-nutritive sucking bouts and greater non-nutritive sucking duration compared with calves fed 1 portion/d.	=[4]	Jongman et al., 2020[5]
Automated milk feeding										
4 portions/d; 8 portions/d	192	HF, DR, JER	Group (24 vs. 12)	6.4 (HF and DR) 4.8 (JER)	Prewean: 12–70	CS NNTeat	Behavior was recorded continuously (using video) during 24 h for each block of calves when the youngest calf was at least 21 d and before the oldest calf was 70 d.	No effect of milk feeding frequency. Calves that had their daily allowance distributed into 8 portions/d spent more time NNTeat at the milk feeder compared with calves given 4 portions/d.	= =[4]	Jensen, 2004
4 portions/d; 8 portions/d	40	HF, DR, JER	Group (16)	6.4 (HF and DR) 4.8 (JER)	Prewean: 6–10; 14–29	CS NNTeat	Behavior was recorded for 8 h on d 1, 8, and 15 following the introduction to the group pen. Calves entered the group pen on d 6 or 14 of age.	No effect of milk feeding frequency. Calves offered 8 portions/d spent more time NNTeat compared with calves offered 4 portions/d (26.2 ± 2.03 vs. 18.8 ± 2.03 min/8 h).	= =[4]	Rasmussen et al., 2006[6]
2 portions/d; 4 portions/d	10	HF	Group (10)	8	Prewean: 3–62 Postwean: 63–70	CS NNTeat at milk teat	Behavior was continuously recorded (using video) from 0800 to 1400 h and 1800 to 2400 h 1 d/wk from wk 4 to 10, yielding 84 h of observations per calf.	No effect of milk feeding frequency. No effect of milk feeding frequency.	= =	MacPherson et al., 2019
Large but few meals; Small but many meals	64	HF	Group (8)	8; 6 maximum milk allowance (total milk offer was similar)	Prewean: 12–56 Postwean: 57–70	NTeat/NNTeat OtherOral at milk teat[7]	Behavior was recorded continuously (using video) during 24 h/d on 26 d and 40 d of age.	No effect of milk feeding frequency. Calves offered small but more portions per day spent less time standing in the automated feeder and manipulating the teat than calves offered large but fewer portions per day.	= +	Jensen et al., 2020

[1]HF = Holstein-Friesian; DR = Danish Red; JER = Jersey.

[2]See Table 1 for descriptions of abbreviations. "/" between 2 terms indicate authors grouped these behaviors into one category.

[3]Effects are presented for increasing feeding frequency with respect to low feeding frequency. Effect direction: "+" indicates that the effect was interpreted as positive or desirable and "−" as negative or undesirable. Studies are ordered chronologically by year.

[4]Effect interpreted as neutral. Sucking behavior is stimulated each time the calf ingests milk irrespective of portion size.

[5]Additional treatment assessing milk allowance. Results are presented in Table 3.

[6]Additional treatment assessing age of introduction to the group pen. Calves entered the group pen on 6 or 14 d of age.

[7]Authors measured time that calves spent manipulating the teat, which was considered actively pushing, butting, or biting the teat while in the automated feeder.

were of an experimental design investigating 1 versus 2 portions/d (Saldana et al., 2019) and 2 versus 3 portions/d (Grice et al., 2020) on diarrhea and respiratory disease. The final study used a cohort study design measuring incidences of diarrhea and respiratory disease on 492 calves across 11 farms (Johnson et al., 2021a).

DISCUSSION

This systematic review evaluated a wide range of studies that explored the effects of milk feeding practices on behavior, health, and performance. The majority of studies focused on milk allowance (73%) followed by milk feeding methods (15%) and milk feeding frequency (15%). We caution that only studies written in English and those that were available online or through Aarhus University library were included in the data synthesis. Thus, this review may bias toward North American and European management and may not represent all milk feeding practices implemented worldwide.

Milk Allowance

The majority of studies (90%) reported that increased milk allowance improved growth during the preweaning period. However, mixed results were found during the weaning and postweaning period, where 40% of studies reported a reduction in ADG during weaning in high-milk-fed calves, and 47% of studies reported that high-milk-fed calves were unable to maintain their weight advantage postweaning. These results are likely due to the influence of milk allowance on starter intake. The majority of studies (74%) reported that increased milk allowances suppressed starter intake during the preweaning and weaning periods, mirroring results on milk and starter meal duration, where calves fed high milk allowances spent more time ingesting milk and less time eating starter. Calves are born pseudo-monogastric and are completely reliant on milk as their source of energy and nutrition during the first 4 wk of life (Diaz et al., 2001). It is also important to facilitate starter intake during the preweaning period to promote rumen development and ensure a smooth weaning transition onto solid feed (reviewed by Khan et al., 2016). Calves fed a high milk allowance likely had poor rumen development and were unprepared for milk removal, resulting in reduced growth or weight loss during weaning. Implementing a gradual weaning method after 4 wk of age can increase solid feed consumption before complete milk removal, allowing time for the rumen to mature. It is recommended that calves be weaned at later ages (>8 wk) and gradually over several weeks (>2 wk) to increase starter intake, minimize low growth, and reduce signs of hunger around weaning (Khan et al., 2007; de Passillé et al., 2010; Eckert et al., 2015). Indeed, out of the 3 studies that reported a positive or desirable effect of milk allowance on preweaning starter intake (or over the experimental period), 2 studies used a step-up, step-down milk feeding plan when feeding high milk allowances where calves were gradually weaned over approximately 20 d (Omidi-Mirzaei et al., 2015; Valehi et al., 2022), whereas the third study weaned calves based on individual starter intake (Byrne et al., 2017). Weaning based on individual starter intake has the advantage of ensuring that each calf consumes a minimum level of starter before milk allowance is reduced, thus increasing the likelihood that calves are nutritionally ready for the transition (Welk et al., 2022). Overall, feeding high allowances of milk improves growth during the preweaning period and, when coupled with gradual weaning methods, this growth advantage can be maintained into the postweaning period (Khan et al., 2007; de Passillé et al., 2010; Eckert et al., 2015).

Few studies examined the effect of milk allowance on sucking behaviors (14%), with little effect of milk allowance found, particularly on abnormal sucking behaviors (i.e., cross-sucking, non-nutritive sucking on pen fixtures, and other oral behaviors). Lack of findings could be related to methods used to assess behaviors, which were inconsistent across studies and often used a short observation time. For example, Jensen and Budde (2006) only recorded cross-sucking for 30 min after milk feeding on 3 occasions (wk 2, 4, 6), and Hosseini et al. (2019) recorded other oral behaviors for 6 h in the week before weaning. De Paula Vieira et al. (2008), Todd et al. (2018), and Jongman et al. (2020) measured sucking behaviors for only 72 h during the first week of life, which may be problematic as some young calves are adjusting to higher milk allowances during this time. In addition, definitions of sucking behaviors varied across studies. To categorize behaviors, we defined 5 sucking behaviors commonly observed in experimental studies; however, some studies combined some or all of these behaviors, making interpretation difficult. For instance, if sucking at a teat (an outlet for sucking motivation) and cross-sucking (an abnormal behavior) are combined, the results cannot be interpreted in terms of animal welfare. Many studies also grouped nutritive and non-nutritive sucking of a teat; however, these may contribute differently to the satisfaction of the behavioral need. Therefore, we encourage researchers in future studies to carefully define sucking behaviors and avoid grouping these behaviors together to facilitate interpretation of results.

Three (out of 5) studies did show an increase in non-nutritive sucking directed at the milk teat in calves fed lower allowances of milk. Although non-nutritive

sucking directed at the milk teat after a milk meal is a natural behavior in calves (de Passillé and Rushen, 2006), excessive non-nutritive sucking at the milk teat may be a sign of hunger (de Passillé and Rushen, 1997; Herskin et al., 2010). These results are supported by our finding on unrewarded visits to the milk feeder, where 87% of studies found a decrease in unrewarded visits in calves fed higher milk allowances. Taken together, these results indicate that feeding calves low milk allowances increases behavioral signs of hunger. One benefit of using milk feeders to measure behavioral signs of hunger is that data can be collected continuously over the experimental period, allowing for a better understanding of how behaviors change over time. Nevertheless, these automatically recorded data should be supplemented with behavioral observations of oral behaviors such as cross-sucking, as well as oral behaviors in the milk feeder to help interpret the various types of visits a calf pays to the milk feeder (e.g., De Paula Vieira et al., 2008; Nielsen et al., 2008).

Play behavior appeared to be influenced by milk allowances, with all studies that measured locomotor play (n = 4) finding a positive or desirable effect of higher milk allowance. The reduction in play found in calves fed a low milk allowance cannot be explained by decreased activity, as we also found some evidence that calves fed low milk allowances spent less time lying (i.e., more time standing) compared with calves fed high milk allowances (De Paula Vieira et al., 2008; Borderas et al., 2009). Größbacher et al. (2020) found that locomotor play peaked around feeding time and suggested that milk ingestion stimulates a positive affective state of high arousal, resulting in increased motivation to perform play behavior. Digestible energy intake was found to be positively correlated with time spent playing (Krachun et al., 2010; Jensen et al., 2015); possibly, calves have a higher tendency to play when satiated. In addition, play is reduced by welfare threats, such as pain and hunger (Held and Špinka, 2011), which may also explain the lower levels of play in restricted-milk-fed calves. It was noted that locomotor play behavior decreases with age in later weeks (Krachun et al., 2010). This may explain why some studies investigating milk feeding frequencies and milk feeding methods reported no differences in play, such as Webb et al. (2015), who measured locomotor play at 15 and 24 wk of age. Overall, play behavior, which has been suggested an indicator of a positive affective state (Boissy et al., 2007; Held and Spinka, 2010), appears to be influenced by milk allowance.

Milk allowance had little effect on health, with 62% of studies that measured diarrhea, 91% of studies that measured respiratory disease, and 100% of studies that measured mortality finding no effect. However, 19% of studies that measured diarrhea reported increases in diarrhea in calves fed higher milk allowances (Osorio et al., 2012; Dennis et al., 2018b; Gerbert et al., 2018; Scoley et al., 2019; Suarez-Mena et al., 2021). Higher fecal scores and more days with diarrhea due to more milk being fed to calves have been a concern in the industry (Quigley et al., 2006). However, this may relate to the concentration of the milk replacer rather than the amount. Indeed, all studies reporting an increase in diarrhea with increasing milk allowance used milk replacer. Currently, the effect of concentration of milk replacer on fecal scores is unclear; however, milk replacers are typically fed at higher total solids compared with whole milk. A higher percentage of milk solids creates an osmotic gradient that causes absorption of fluid into the intestinal lumen, potentially leading to looser fecal matter (McGuirk, 2008; Wilms et al., 2019). It is also important to distinguish between loose fecal matter and pathogenic diarrhea. The majority of studies (16 of 26) defined what constitutes diarrhea and reported either days with diarrhea, number of calves with diarrhea, or risk of being diagnosed with diarrhea; however, 10 studies simply reported mean fecal scores. It is important to emphasize that an elevated fecal score does not indicate diarrhea. Calves fed higher amounts of milk are likely to have looser fecal matter due to an increase in water intake from the milk. Indeed, 3 of the 5 studies reporting increases in diarrhea in calves fed higher milk allowances reported mean fecal scores and did not define diarrhea. Overall, milk allowance had little effect on health; however, caution is needed when interpreting results, as health was a secondary outcome in the majority of studies, and sample size calculations for health outcomes were not provided. These limitations also apply to studies assigning the effects of milk feeding method and feeding frequency on health.

One potential limitation is that milk allowance was reported in liters fed per day, in order to standardize milk allowances across studies. However, reporting in liters per day does not take into consideration milk composition and percent of total solids, which vary across whole milk and milk replacers. Milk composition and percent of total solids will likely influence feed intakes, growth, and potentially health; however, its influence on behavior is unclear. A more appropriate way of reporting milk allowance is in metabolized energy allowed for growth (Soberon et al., 2012). This measurement takes into consideration how much metabolizable energy is left for growth after energy needed for maintenance has been met, an important factor when considering climatically different conditions. Many articles included in this review lacked detailed reporting of milk allowances and milk composition, and overall better reporting of this information is encouraged. In particular, reporting

of percentages of fat, protein, and lactose in whole milk or milk replacer, as well as percent of total solids, liters fed per day, and metabolized energy could be improved.

Milk Feeding Method

Milk feeding method had the greatest effect on cross-sucking, with bucket-fed calves performing more cross-sucking than teat-fed calves. Similarly, studies measuring non-nutritive sucking on pen fixtures or other oral behaviors (n = 4) reported that feeding milk by a teat reduced the occurrence of these behaviors. Teat-fed calves also spent more time ingesting milk than bucket-fed calves (nutritive sucking) and preferentially directed their non-nutritive sucking toward the milk teat. These results indicate that feeding calves milk by teat provides an outlet for their sucking motivation (Rushen and de Passillé, 1995) and satisfies their behavioral need to suck, whereas offering milk by bucket does not. However, few studies measured how milk feeding method affected behaviors related to hunger (i.e., vocalizations and unrewarded visits at the milk feeder).

No study in this review provided an appropriate experimental design to test the effect of a dry teat on cross-sucking and abnormal oral behaviors. Salter et al. (2021) did find that providing a Braden bottle (a teat bottle filled with calf starter) reduced cross-sucking and other oral behaviors in bucket-fed calves, but bucket-fed calves with access to a Braden bottle performed more cross-sucking and other oral behaviors compared with teat-fed calves. Salter et al. (2021) provides some evidence that providing calves with a dry teat will reduce cross-sucking and abnormal oral behaviors in bucket-fed calves; however, feeding calves though a milk teat provides the most benefits. In support of this, calves appear to favor the milk teat over the dry teat, as they spent more time non-nutritive sucking at the milk teat compared with the dry teat (Hammell et al., 1988; Jung and Lidfors, 2001) and compared with a Braden bottle (Salter et al., 2021). Future work should apply the study design by Salter et al. (2021) to a dry teat to investigate the effect of a dry teat on non-nutritive sucking following milk ingestion, as well as abnormal oral behaviors.

Milk feeding method did not appear to influence health. There was some evidence that bucket-fed calves or calves fed manually had more cases of diarrhea (Bernal-Rigoli et al., 2012; Sinnott et al., 2021); however, both studies failed to define diarrhea and only reported overall mean fecal scores. As previously mentioned, increased fecal scores do not mean increased diarrhea; thus, results from the latter studies should be interpreted with caution. Automated milk feeding has been associated with increased risk for disease (Svensson et al., 2003). In this review, 3 studies assessed health in automated versus manual feeding methods; however, health was a secondary outcome and sample size within these studies was low (≤30 calves per treatment), making it difficult to interpret results. Care must also be taken when comparing these 2 milk feeding systems as group size can be a confounding factor, where groups are typically larger in automated feeding systems (Svensson et al. 2003). More research is needed to understand how milk feeding method affects health.

Milk Feeding Frequency

Few studies examined the effect of milk feeding frequency (n = 6) on sucking behaviors, making it difficult to draw strong conclusions. Feeding frequency did not appear to influence cross-sucking or non-nutritive sucking at pen fixtures when automated feeders were used. However, 24-h access to a teat in automated milk feeding systems may have enabled calves to satisfy their need to suck, thus reducing the risk of these abnormal behaviors. In terms of non-nutritive sucking at the teat, a higher feeding frequency was found to increase this behavior. This finding is in accordance de Passillé and Rushen (1997), who found that non-nutritive sucking is stimulated every time the calf ingests milk; therefore, offering the same milk allowance in more daily portions results in more non-nutritive sucking at the teat on a daily basis. In addition, sucking the teat after milk intake is a natural behavior for calves and is often observed in calves reared by the dam (de Passillé and Rushen, 2006). Overall, these results suggest that if increased milk feeding frequency is associated with an opportunity to perform non-nutritive sucking on a teat, this will not result in abnormal sucking behaviors, such as cross-sucking and non-nutritive sucking on pen fixtures.

Only 2 studies assessed behavioral signs of hunger in relation to milk feeding frequency, with conflicting results reported (Jensen, 2004; MacPherson et al., 2019). However, other studies within this review reported behaviors that may be indicative of hunger. Jafari et al. (2021) found that calves fed 3 milk portions/d compared with 2 milk portion/d consumed less starter during the preweaning period (5 to 55 d). This aligns with results from Jensen et al. (2020), who found that calves with reduced milk meal frequency spent more time eating starter. Having fewer meals may leave calves hungry during more of the day, motivating calves to find alternative feed sources. This may also explain findings by Sinnott et al. (2021), in which calves fed manually in 2 portions/d had greater starter intake than calves fed by automated feeders (programed to offer 4 portions/d). Jensen et al. (2020)

also found that calves fed fewer milk portions spent more time manipulating the teat and spent more time in the milk feeder, behaviors that have been linked to hunger (Jensen, 2004; De Paula Vieira et al., 2008). Taken together, these findings suggest that calves with lower milk feeding frequency (i.e., <2 or 3 portions/d depending on calf age) experience higher feeding motivation and possibly hunger, warranting further research on this topic.

This review highlighted some evidence that calves with lower feeding frequencies consume less milk, particularly at younger ages. For example, Jongman et al. (2020) found that milk intake was reduced by approximately 50% on d 3 and 20% on d 4 of age in calves fed 4.4 L/d in 1 portion/d compared with calves fed the same milk allowance but in 2 portions/d. This suggests that 1-wk-old calves cannot ingest this milk allowance in one meal and that a period of adaptation may be required for calves to adjust to less frequent milk feeding. In a similar study not reported in this review, Muya and Nherera (2014) found that at 2 wk of age, calves ingested on average 8 L/d and 6 L/d when offered 2 portions/d and 1 portion/d, respectively, which suggests that 2-wk-old calves cannot ingest more than 6 L of milk in one feeding. Together, these results suggest that calves under 4 wk of age are likely unable to consume high volumes of milk in one feeding. Thus, calves fed at lower feeding frequencies (i.e., 1 portion/d) may not be able to achieve similar milk intakes as calves fed greater feeding frequencies. Feeding milk in 2 meals/d is the most common practice in the industry (Reipurth et al., 2020; Johnsen et al., 2021b). However, only a handful of studies investigating feeding frequency (n = 4) fed milk at or above 8 L/d. As the industry shifts from feeding small to large quantities of milk to calves, we need a better understanding how feeding frequency affects behavior and performance at these milk levels.

When reared by the dam, calves typically suckle from the dam 8 to 12 times/d during the first few weeks of life, consuming small quantities of milk at each feeding (reviewed by Whalin et al., 2021). However, as calves age, their feeding behavior shifts to consuming large quantities of milk over fewer meals (Das et al., 2000). There is currently limited understanding of how feeding frequency affects calves at different ages. Only one study in this review assessed reducing feeding frequency from 2 portions/d to 1 portion/d at 14 or 28 d of age with no effects on feed intakes, growth, or health; however, behavior was not measured. Further research is needed to understand the optimal milk feeding frequency for calves in both manual and automated feeding systems when fed high allowances milk and how feeding frequency affects calves at different ages.

CONCLUSIONS

The literature investigating milk feeding practices has primarily focused on milk allowance. Increasing milk allowance can improve growth preweaning. Although preweaning starter intake is suppressed by high milk allowances, using gradual weaning methods can facilitate starter intake and allow high-milk-fed calves to maintain their growth advantages postweaning. In addition, increasing milk allowance reduces behavioral signs of hunger (e.g., unrewarded visits to automated milk feeder) and promotes locomotor play behavior, which can be an indicator of positive affective states. Studies assessing calf health pointed to no effect of milk allowance; there was no consistent evidence indicating increasing milk allowance results in higher fecal scores. However, health was a secondary outcome in the majority of studies. Epidemiological study designs that provide adequate sample size calculations are needed to fully understand the effect of milk feeding practices on calf health. Feeding milk with a teat can reduce cross-sucking and abnormal oral behaviors by providing an outlet for calves' motivation to suck. However, the behavioral effects of access to a dry teat were mixed, indicating that further research is needed to better assess if a dry teat provides an adequate outlet for sucking motivation and meets calves' behavioral need to suck. Few studies investigated milk feeding frequency, making it difficult to draw strong conclusions. Feeding frequency appeared to have little effect on feed intakes and growth; however, some evidence suggests that calves with lower feeding frequency experience hunger. Future work is needed to determine the optimal feeding frequency for dairy calves at different ages.

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