J. Dairy Sci. 106:8835–8846
https://doi.org/10.3168/jds.2022-23099

Proposed methods for estimating loss of saleable milk in a cow-calf contact system with automatic milking

Mikhail Churakov,[1,2] Hanna K. Eriksson,[1] Sigrid Agenäs,[1,2] and Sabine Ferneborg[3]*
[1]Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences (SLU), 750 07 Uppsala, Sweden
[2]Beijer Laboratory for Animal Science, Swedish University of Agricultural Sciences (SLU), 750 07 Uppsala, Sweden
[3]Department of Animal and Aquacultural Sciences, Faculty of Biosciences, Norwegian University of Life Sciences (NMBU), NO-1432 Ås, Norway

ABSTRACT

Cow-calf contact (CCC) systems, although beneficial in many respects, introduce additional challenges to collect reliable data on milk production, which is important to assess individual cow efficiency and dairy farm profitability. Apart from weighing calves before and after each feeding, the amount of saleable milk lost due to calf suckling is practically impossible to measure. Here, we assess 2 indirect methods for estimating loss of saleable milk when housing cows and calves together in a robotic milking unit. In our study, treatment (CCC) cows and calves were kept together full time until the calves were 127 ± 6.6 d old (mean ± SD). Control cows were separated from their calves within 12 h of birth and then kept in the same unit as the treatment cows but with no access to either their own or treatment calves. Milk yield recording of both groups was performed from calving until pasture release at 233 ± 20 d in milk. The first estimation method relied on observed postseparation milk yield data, which were fed into a modified Wilmink regression model to determine the best-fitting lactation curve for the preseparation period. The second method was based on the cows' daily energy intake postseparation, calculated by measuring the daily feed intake and analyzing the energy content of the ration. The calculated energy intake was used to determine the average ratio between energy intake and the observed milk yield the following day for each individual cow, assuming constant rates of mobilization and deposition of body fat. The obtained ratio was then used to calculate the expected daily milk yield based on daily energy intake data during the preseparation period. In this paper, we analyzed data from 17 CCC cows kept together with their calves and 16 control cows; both groups calved from September to October 2020 and were followed up until release to pasture in May 2021. Saleable milk yield was lower in CCC cows than in control cows, both before and after separation. The 2 methods were used on data for control cows and showed milk yield loss using the lactation curve method (average of −3.4 ± 2.8 kg/d) and almost no loss using energy intake data (average of −1.4 ± 2.7 kg/d). Milk yield loss for CCC cows was estimated at average 11.3 ± 4.8 and 7.3 ± 6.6 kg milk/d, respectively. The proposed lactation curve estimation method tends to overestimate milk yield loss, whereas the method based on energy intake is more accurate. However, collecting detailed energy intake data per individual cow requires additional effort and equipment, which is not always feasible on commercial farms. Further research is needed to improve milk loss estimation and to better understand trade-offs in CCC systems.
Key words: dam rearing, suckling, lactation curve modeling, AMS

INTRODUCTION

The practice of keeping cow and calf together, cow-calf contact (**CCC**; Sirovnik et al., 2020), in modern dairy production is attracting interest from farmers as well as consumers around the world (Eriksson et al., 2022; Sirovica et al., 2022). Although studies of the practice have been conducted over the course of the last 30 years, the practice, as well as some of the challenges that accompany it, is still at an early research stage, and we have much to learn about short- and long-term effects on cows and calves.

A major source of concern for farmers considering CCC is the loss of saleable milk and the subsequent decrease in revenue for the farm. However, very few studies have been conducted on the effects on milk yield in different types of CCC systems (Meagher et al., 2019; Barth, 2020; Nicolao et al., 2022). Loss of saleable milk can have several explanations. In addition to milk consumed by the calf, it is possible that saleable yield becomes limited due to disturbed milk ejections leading to decreased milk removal (Zipp et al., 2018). It is also possible that other factors, for example lower energy intake, limit the milk yield for CCC cows (Agenäs et al., 2003).

Received December 2, 2022.
Accepted May 12, 2023.
*Corresponding author: sabine.ferneborg@nmbu.no

Eriksson et al. (2022) reported that a large variety of housing, milking, and management systems are used on European CCC farms, which may affect the lactation curve and, hence, the amount of saleable milk lost. For example, Barth (2020) found that the amount of pre-separation contact affected saleable milk yield before and after separation, as cows that were kept with calves only during nighttime reached the production level of control cows after separation, whereas cows with whole-day or short-time contact produced less saleable milk both before and after separation.

Zipp et al. (2018) found that CCC cows delivered less saleable milk and had lower milk flow and lower fat content in milk during the period with calf contact, compared with cows separated from their calves within 12 h after calving. These findings indicate a less efficient milk ejection response to machine milking in the CCC cows, which could possibly be due to insufficient oxytocin release during milking (de Passillé et al., 2008). As the milk synthesis rate is highly influenced by milk accumulation in the mammary gland (Dutreuil et al., 2016), milk remaining in the udder after milking can negatively affect milk synthesis due to milk accumulation in the secretory tissue. Incomplete or infrequent milk removal can have a negative effect that carries over to several milkings (Albaaj et al., 2018), or even for longer periods (Loiselle et al., 2009), potentially leading to lower long-term milk yields in CCC cows. However, Bar-Peled et al. (1995) reported that both increasing machine milking frequency and allowing short-duration suckling between milkings during early lactation increased milk yield during the 6-wk study period, compared with cows milked 3 times per day. In addition, Carbonneau et al. (2012) showed that once-daily milking in combination with suckling during the first 5 d after calving did not negatively affect daily milk yield during early lactation, as opposed to the findings of Loiselle et al. (2009), who reported that cows milked once daily during the first week had lower milk yield for at least 14 wk postpartum, compared with control cows milked completely twice per day from calving and onward.

A first step in evaluating the effects of CCC on lactation milk yield is to provide accurate estimates of the total amount of milk that the cow produces during the time with calf contact. Because determination of milk intake by the calf can be challenging (de Passillé et al., 2008) and the amount of milk consumed varies between calves (Scholz et al., 2001), estimation of true total milk yield is not as straightforward in CCC systems as it is in conventional milk production. Although several methods are available to estimate milk intake in the offspring, such as weigh-suckle-weigh and deuterium oxide marker (Prawirodigdo et al., 1990), these methods have been developed to estimate milk intake in the young rather than milk production in the mother. In addition, both methods can be stressful and cause disturbances to mother-offspring interactions, and are further complicated by allosuckling, making them unfeasible in many CCC systems.

As such, we need new strategies to estimate actual milk production, to be able to assess the true costs and benefits with CCC. Accurate milk yield estimates could inform farmers on how to improve management of cows in CCC systems to maintain herd profitability, including selection of animals to be bred again. Energy intake and milk yield are closely related, making it feasible to estimate milk yield from energy intake and other sources of energy expenditure (Agenäs et al., 2003; Volden, 2011). However, this requires detailed data that may not always be available on farm, and is sensitive for missing data. Previous studies on lactation curve estimation have developed models that can be used to predict the total lactation yield based on data points early after parturition, to speed up decisions for genetic selections (Druet et al., 2003). Lactation curve modeling has also been used to determine when individual cows should be inseminated (Bertilsson et al., 1997; Swalve, 2000). However, a similar approach that is robust to missing data could be used to reconstruct unobserved milk yield data retrospectively.

Our study aims were to propose new ways to estimate saleable milk loss due to calf suckling. We used 2 different methods to estimate milk loss: milk yield prediction through lactation curve estimation and milk yield prediction using energy intake data.

MATERIALS AND METHODS

Study Design

The study was conducted at the Swedish Livestock Research Centre, Uppsala, Sweden, between September 1, 2020, and May 20, 2021. All experimental procedures and animal handling were approved by the local ethics board in Uppsala, Sweden (ID no. 5.818-18138/2019), following EU regulations.

Data analyzed in this study were collected in a trial comparing early separation between cow and calf with a minimum CCC period of 16 wk (115–139 d, with the mean of 126 DIM). Initially 40 cows were selected for the trial and assigned to control (early separation) or treatment (CCC) groups. The dams of every other heifer and bull calf were assigned to either of the groups, balancing them based on age and sex of calves and, as far as possible, also on breed and parity of dams. Four cows were removed from this study because they had mastitis at any point during the study period, since mastitis can cause long-term reduction in milk production. One additional CCC cow was removed because her calf was euthanized after a trauma, resulting in a total of 18 control cows and 17 CCC cows. We excluded 2 additional cows because they were culled due to high SCC (1 CCC cow) and teat injury combined with low production (1 control cow) several months before pasture release. Thus, the final data set used in this publication contained data from 16 control and 17 CCC cows, representing 2 breeds: Swedish Red (n = 20) and Swedish Holstein (n = 13), in parity 1 (n = 19) or higher (n = 14). The cows were labeled according to their group (C = control, T = treatment, i.e., CCC), their breed (H = Swedish Holstein, R = Swedish Red), and their parity number plus a running number within each parity starting from zero (e.g., CR40 is a control cow of Swedish Red breed in its fourth lactation). The summary of the cows enrolled in the study is presented in Supplemental Table S1 (https://data.mendeley.com/datasets/rh2ffng924/1; Churakov et al., 2023).

Housing and Management

Cows calved in individual pens (3 × 4 m). In the control group, cows and calves were separated within 12 h of parturition. Control calves were then reared in indoor group pens with ad libitum access to water, hay, silage, and concentrate. They were also individually fed 9 L of whole milk per day in buckets with artificial teats and weaned at approximately 10 wk of age using a step-down protocol. The treatment cow-calf pairs stayed in the individual calving pen 2 to 3 d after parturition. During the days in the individual calving pen, the calf was allowed to suckle freely, and the cow was bucket-milked twice daily.

When control cows and CCC pairs were moved from the calving pen, they were introduced to a unit for automatic milking (DeLaval VMS, DeLaval International AB, Tumba, Sweden; **VMS**) with semi-controlled Feed First (DeLaval International AB, Tumba, Sweden) cow-driven traffic system (Figure 1). Cows were not regularly driven to milking. Cows had access to silage ad libitum in feed troughs, and concentrate was offered in automatic feeders according to the NorFor calculated requirement (Volden, 2011) based on each cow's individual milk yield. The CCC cows were assumed to have an average milk production for their breed and parity during the contact period. After the contact period, CCC cows were kept on the same ration for 2 additional weeks before concentrate was adjusted to actual production. The unit had concrete floors that were cleaned with mechanical scrapers. Cubicles were equipped with rubber mattresses (M40R, DeLaval International AB, Tumba, Sweden) and bedded with wood shavings.

The CCC calves had access to a calf creep and a contact area where they could meet CCC cows. In the calf creep they had ad libitum access to water, hay, silage, and concentrate. When cows (both control and CCC) left the roughage eating area, they entered a 3-way selection gate (DeLaval Smart Selection Gate SSG, DeLaval International AB, Tumba, Sweden) that directed them to milking if they had milking permission, or to areas with cubicles. For CCC cows, this meant that they were directed to a part of the unit that calves had access to (the contact area). In the contact area, cows had access to concentrate feeders, cubicles, other CCC cows, and the calves. Cows could leave the contact area at any time and access cubicles that calves did not have access to or go to the roughage area. In addition to the cows included in the trial, other cows were present in the automatic milking system (**AMS**) unit to fill it to its capacity. The maximum number of cows in the AMS during the trial was 58. Only cows in the CCC treatment group had direct access to the calves, but all cows in the unit could see, hear, and smell the calves. Seven of the cubicles that were available for all cows allowed nose-to-nose contact with calves through barriers. Calves in the unit could see, hear, and smell other cows but only had direct access to the CCC cows.

Weaning and Separation

To avoid cumulation of multiple stressors, the CCC calves were weaned before they were separated from their dams. To address a separate line of inquiry, the calves were divided into 2 groups according to age and weaned at approximately 16 wk of age using 2 different weaning procedures. The first-born group were equipped with nose-flaps (QuietWean, Saskatoon, Canada) for 14 d before separation, whereas the second group were equipped with nose-flaps for 7 d followed by 7-d fence-line contact. After separation, all cows and calves were managed according to standard routines at the farm, which meant that farm staff could move cows to other VMS units (in total 4 different VMS units available) to facilitate herd management. All cows remained in the original VMS unit until at least 145 DIM. In total, 15 of 17 CCC cows and 10 of 16 control cows remained in the same unit until pasture release, Of the moved animals, 1 CCC and 3 control cows were moved once, and 1 CCC and 3 control cows were moved twice before the onset of the pasture period. The size, layout, and cubicles were similar between all VMS units. However, another type of milking unit (DeLaval VMS V300,

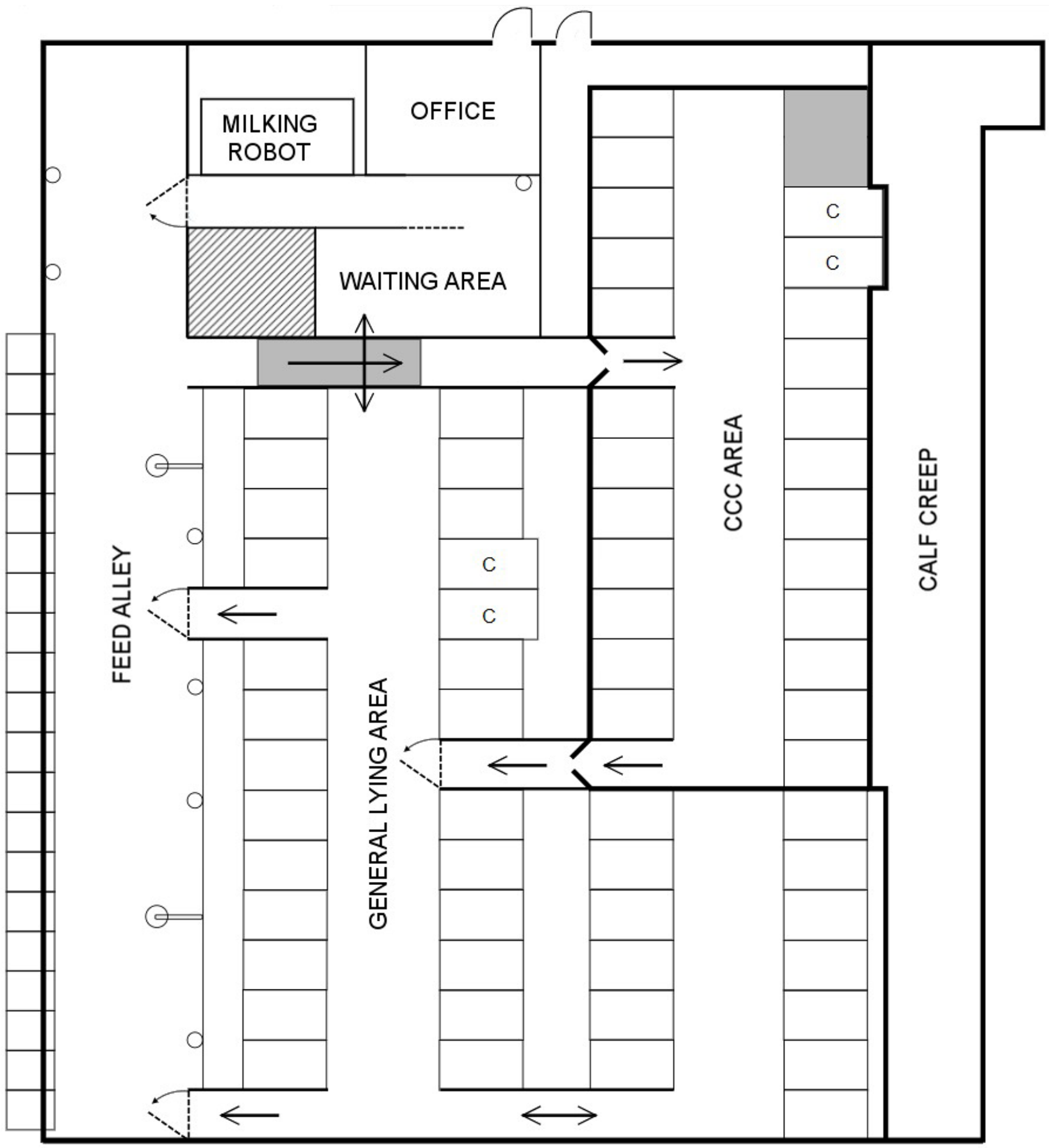

Figure 1. Design of the automatic milking system unit where the animals were housed during the period when the calves were suckling (the contact period). Only cows that had contact with their calves could enter the cow-calf contact (CCC) area, but all cows could access the other parts of the unit. The calves had access only to the calf creep and the CCC area. Arrows indicate direction of movement for the cows; control cows were directed to the right, toward the general lying area, if they did not have milking permission when passing the 3-way selection gate by the waiting area. (Figure by Wegner and Ternman, 2023.)

DeLaval International AB, Tumba, Sweden) was used in the other VMS units (with the same settings), and individual roughage intake could not be measured.

Milk Data

Quarter-level uncorrected milk production in kilograms was recorded at every milking in the VMS throughout the experiment. Milk production was not measured during days cows were housed in the calving or sick pens. Full lactation milk data were retrieved for each control and CCC cow though the farm management platform (DelPro, DeLaval International AB, Tumba, Sweden). However, data collected after the cows were released to pasture were not included in the analyses, because the changes in diet and behaviors related to this event can negatively affect milk yield levels. Initial visual assessment revealed no differences in quarter-level milk yield variation before and after separation (i.e., the calves did not systematically favor a particular teat during suckling; Supplemental Figure S1, https://data.mendeley.com/datasets/rh2ffng924/1;

Churakov et al., 2023), so whole-udder data were used in the analyses.

Energy Intake

In addition, we obtained feed intake data that were used to estimate daily energy intake during the study period. The roughage feed bins (BioControl's CRFI, BioControl AS, Rakkestad, Norway) measured silage intake for each meal and individual. To avoid problems with erroneous feed intake registrations, the roughage troughs were calibrated weekly during the trial. Although all cows could eat from all roughage bins, a bin could only be accessed by one cow at a time. Concentrate intake per cow and visit was registered in the robot and in the concentrate feeders (FSC400, DeLaval International AB, Tumba, Sweden). Roughage and concentrate samples were analyzed after each change of the ration, and daily intake of metabolizable energy was then calculated based on the feed analysis results and daily feed intake data. Because roughage intake could not be correctly measured after the cows were released to pasture, we only used feed intake data before this point in time in our analyses.

Data Preparation

Data management and statistical analysis were performed in R statistical software (R Core Team, 2019). Descriptive analyses were performed for number of daily visits to the robot, visit intervals, and proportion of incomplete milkings, contrasting group (CCC and control) and period (before and after separation). Results for number of daily visits to the robot at group level are based on the mean number of daily visits at cow level. Due to skewness in the cow-level milking interval data, results on treatment level for this outcome are based on median cow-level visit interval.

For retrospective estimation of milk yield and milk yield loss before separation, we had 2 sources of data: daily milk yield after separation and energy intake between calving and release to pasture.

Daily Milk Yield Estimation

A common method to derive a cow's daily milk yield from individual milking data is to sum up all milk yield within a given 24-h period. However, this approach can result in unusually high or low values due to milk records that happen close to the start or end of each period (i.e., around midnight). Moving averages (or rolling means) have been used to smooth the lactation curve to avoid misleading daily milk yield estimates. However, in this study we used an alternative approach that takes into account how much time has passed between individual milkings: For each recorded milking, we calculated the expected milk yield per 24 h, assuming constant milk secretion rate since previous milking (i.e., milk yield in kg divided by the time in hours since previous milking and multiplied by 24). This results in a stepwise function (see Figure 2) with a variable number of stepwise estimates per day, depending on the number of times an individual cow was milked within a particular day. These estimates were then averaged for each day to obtain a more precise estimation of daily milk yield, resistant to the timing of individual milkings.

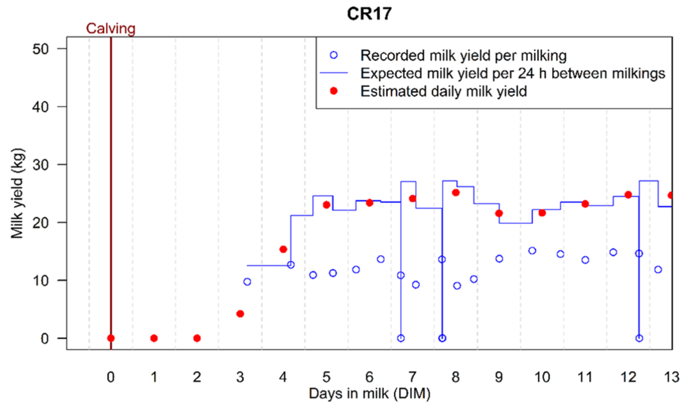

Figure 2. Daily milk yield estimation of 1 Swedish Red control cow (CR17). This illustrative example shows individual milk yield records (blue open circles); expected milk yield per 24 h, assuming constant milk secretion rate between 2 consecutive milkings (blue line); and final estimated daily milk yield (i.e., the average of the milk secretion step curve for each day; red filled circles). The figure also shows 3 incomplete milkings when no milk was harvested, after which the cow was resorted and entered the automatic milking system after a very short waiting period.

Estimated Lactation Curve Model

We used a modified Wilmink regression model for lactation curve estimation for individual cows. The original model is described using the following equation: $MY = a + be^{k\ DIM} + c\ DIM$, where MY is the estimated daily milk yield, DIM is the number of days since calving, a, b, c, and k are parameters that are estimated from data, and e is the base of the natural exponential function (Euler's number).

At calving (i.e., DIM = 0) we expected no milk yield, thus $a + b = 0$. Therefore, to force the lactation curve to start at 0, we used this modified 3-parameter Wilmink equation: $MY = a + b\ DIM - ae^{k\ DIM}$.

In the current study, we were particularly interested in evaluating whether milk yield data collected on the CCC cows after separation could be used to estimate daily milk production during the contact period. As pasture access is known to affect milk yield, we only used data before pasture release during model fitting.

To estimate the model parameters (a, b, and k in the above formula) for each individual cow, a range of optimization algorithms can be used to minimize the discrepancies between the model lactation curve and the observed daily milk yield. Here, we used nonlinear least squares regression.

A particular challenge for the CCC cows was that milk yield at peak lactation and the timing of peak lactation, which determine the exponential coefficient k, could not be directly observed, due to suckling. To address this issue, we decided to use full-curve model estimates for the control cows, for which we had true milk yield data before the pasture release, as a basis to create a model that predicts which k-values were realistic for the Wilmink regression lactation curves with given a set combination of a and b parameters.

After peak lactation, daily milk yield generally decreases linearly. During this phase, the lactation curve can be determined almost exclusively by the linear components (intercept a and slope b) as the contribution of the exponential component becomes negligible. As such, a and b were estimated using a linear regression model. Furthermore, the lactation curves from control cows with similar linear parameters (a and b) were used to extrapolate the exponential parameter k for the treatment cows. This was performed using a generalized linear model (**GLM**) with parameters a and b, and response variable k.

The resulting algorithm consisted of 2 steps. First, we estimated full-curve models for the control cows, using nonlinear least squares regression, and created a GLM model describing correlations between lactation curve parameters $k = \text{glm}(a, b)$. Then, for both CCC and control cows, we used only postseparation data to estimate a and b, using robust linear regression. To determine k and obtain the final lactation curve, we used the GLM model from the previous step.

Thus, we had a full-curve model fit from the first step for control cows, which we could compare with the estimated postseparation fit for the same controls from step 2, to evaluate the accuracy of the model. For CCC cows, we only have the "final fit" estimates, based on the postseparation estimates of a and b, combined with estimated k-values from the GLM model. See Figure 3 for an illustrative example of lactation curve estimation based on daily milk yield data.

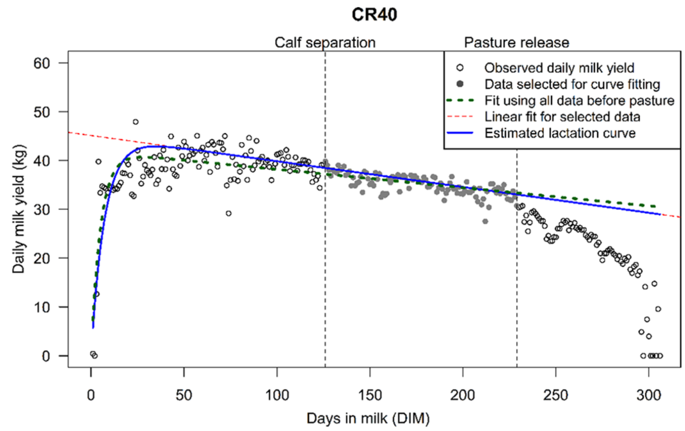

Figure 3. Example of lactation curve fitting for 1 Swedish Red control cow (CR40). For control cows, we first estimated lactation curves on all data before pasture release (heavy green dashed curve). Then, for all cows (treatment and control), we used data between separation and release to pasture (solid dots) to estimate linear parameters (red dashed line) and the final estimated lactation curve (solid blue curve). Open dots represent the observed daily milk yield. For control cows, the separation date was set to 125 DIM (mean contact duration for the cow-calf contact cows).

Milk Yield Estimation Using Energy Intake

For estimation of milk yield based on energy intake, we used daily energy intake data from the previous day for each individual cow. For both CCC and control animals, the ratio between daily milk yield (kg) on the current day and energy intake (MJ ME) on the previous day was predominantly stable. Thus, to get the milk yield estimates, we derived the median (which is less sensitive to outliers than the mean) of the ratio values between separation (or 125 DIM for control cows) and pasture release for each cow and multiplied it by their daily energy intake data to obtain estimates of the following day's milk yield. An illustration of this approach is presented in Figure 4.

Milk Yield Loss Calculation

Once we obtained the estimated daily milk yield levels for the 2 methods, we could calculate discrepancies between observed and estimated data. We decided to present the results as average daily milk yield and milk loss (both in kg), to account for differences in the number of days before or after separation between cows.

RESULTS

Descriptive Results

Before separation, the number of daily visits to the robot was 2.4 ± 0.15 (mean ± SD) for CCC and 2.3 ± 0.23 for control cows, whereas the corresponding values postseparation were 2.4 ± 0.22 and 2.5 ± 0.25, respectively. The preseparation visit intervals were 591 ± 40.8 min for CCC and 626 ± 69.6 min for control cows, but

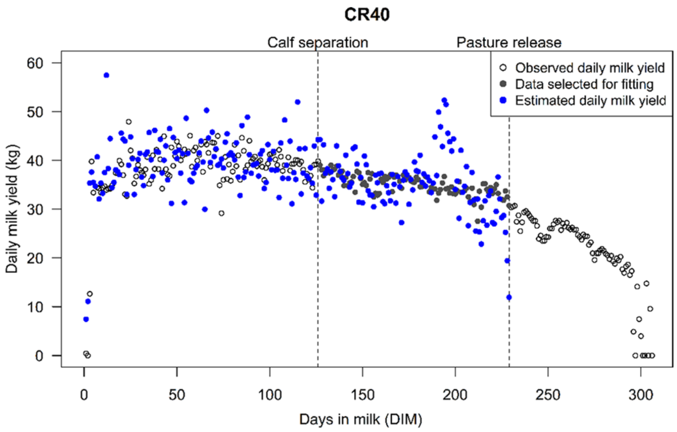

Figure 4. Example of milk yield estimation using energy intake for a control cow. The period between separation (for control cows this was set to 125 d, the mean contact period for cow-calf contact cows) and pasture release (open dots) was used to derive the ratio between milk yield and energy intake on the previous day. This ratio was then multiplied by daily energy intake from calving to pasture release to obtain the estimated milk yield values (solid blue dots) for the full study period.

after separation the intervals were 579 ± 48.6 min and 570 ± 54.0 min for the respective groups. The median (interquartile range) proportion of incomplete milkings (visits when the robot noted that not all quarters had been emptied) was 0.12 (0.079–0.170) for CCC cows and 0.02 (0.011–0.034) for control cows before separation; the corresponding values after separation were 0.02 (0.012–0.065) for CCC cows and 0.01 (0.008–0.028) for control cows.

Milk Yield Loss Estimation Using Lactation Curves

The 2-step lactation curve fitting resulted in estimated values for average daily milk yield and milk loss that are presented in Figure 5. The figure shows results for 2 periods: the period before separation and the period between separation and pasture release, corresponding to before 125 DIM and between 125 DIM and pasture release, respectively, for control cows. This helps to compare inherent errors due to noise in the data (estimates for control cows in the upper-right graph, after 125 DIM) with errors of our method (estimates for controls in the upper-left graph, before 125 DIM). As the estimated milk yield was higher than the observed before 125 DIM, the lactation curve method overestimates saleable milk yield by an average of 3.4 ± 2.8 kg/d. The estimated effect of calf suckling is clearly visible for CCC cows before separation and amounts to an average of 11.3 ± 4.8 kg of milk yield loss per day, not accounting for the overestimation of saleable milk yield discussed above.

Milk Yield Loss Estimation Using Energy Intake

Results for milk loss estimation using energy intake can also be found in Figure 5 (lower graphs). This method is almost unbiased, with estimates of daily milk loss for control cows of −1.4 ± 2.7 kg/d. The effect of calf suckling for CCC cows before separation amounts to an average of 7.3 ± 6.6 kg of milk loss per day.

Comparison of Milk Yield Estimation Methods

Comparison of the 2 milk yield estimation strategies with the observed data is presented in Figure 6. Control cows were estimated to produce more milk than CCC cows, independent of which method was used: 38.9 ± 5.7 versus 31.5 ± 4.9 kg using lactation curve, and 34.1 ± 6.7 versus 27.5 ± 6.1 kg using energy intake. This is partly influenced by the distribution of lactation numbers in both groups (i.e., more primiparous cows among CCC cows). However, even within the primiparous cows we see notable differences in average estimated milk yields: 34.7 ± 2.9 versus 29.2 ± 3.7 kg (lactation curve method) and 34.1 ± 6.7 versus 28.2 ± 6.8 kg (energy intake method), which can be explained by the overall CCC effect.

It is also clear that the lactation curve method tends to overestimate milk yield for control cows and, with few exceptions, exceeds estimates using energy intake for both groups of cows.

DISCUSSION

In this paper, we proposed 2 methods to estimate the losses of saleable milk in CCC systems. This may include milk suckled by the calf as well as possible production losses due to poor milk ejection (Barth, 2020). Results showed that milk yield loss for CCC cows before separation amounted to, on average, 11.3 ± 4.8 kg/d using the lactation curve method and 7.3 ± 6.6 kg/d using the energy intake method. The method utilizing feed intake data was more accurate in estimating milk yield compared with the lactation curve estimation, based on the lower deviation from actual production among control cows.

Several assumptions were made to make the estimations of milk yield. First, we assumed that milk secretion rate was constant between milkings over a 24-h period; second, we limited the data used for the lactation curve estimation to the prepasture period, because the pasture period would have introduced an unwanted source of variation in the data; third, we assumed that milk yield reflected energy intake on the previous day and that the conversion of energy in feed

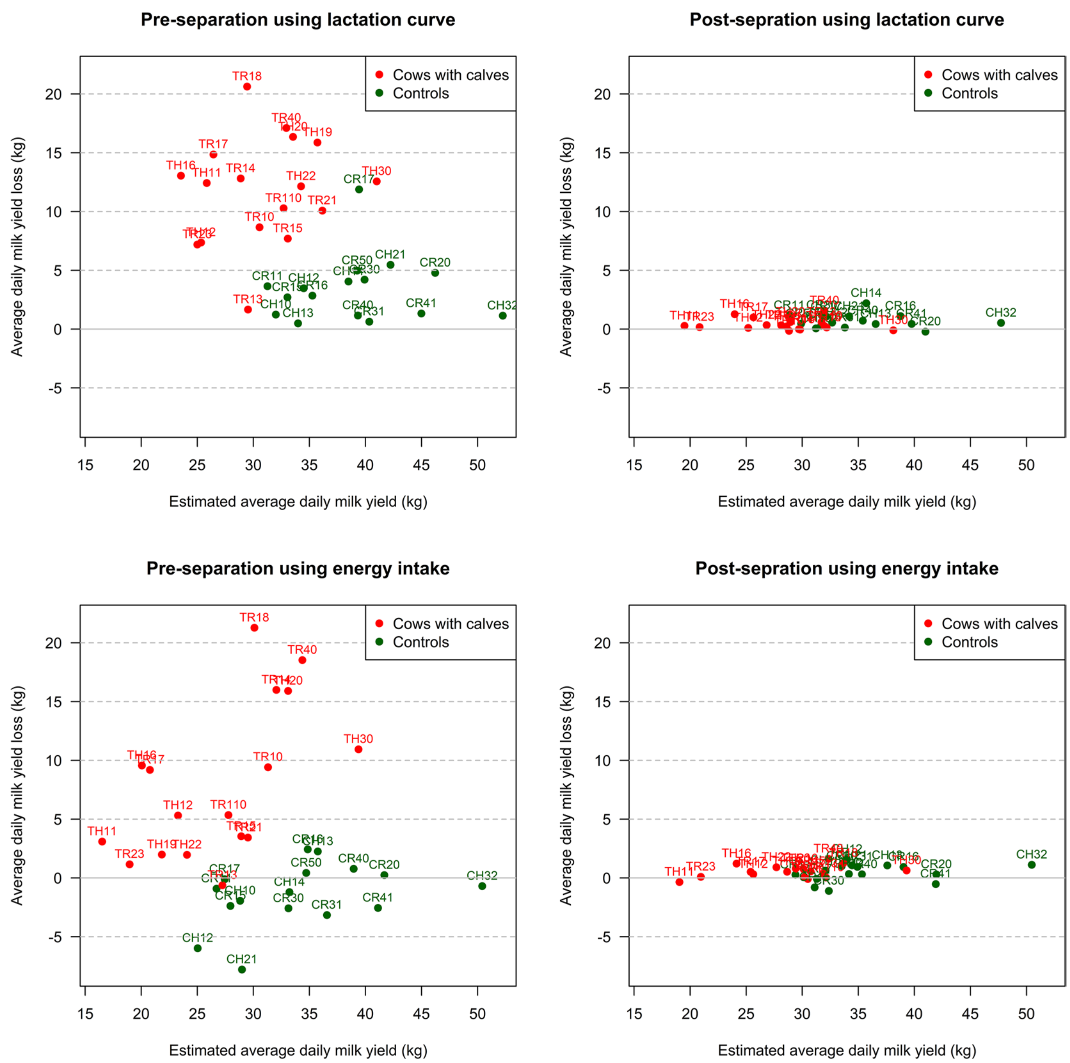

Figure 5. Average daily milk yield loss for control and cow-calf contact (CCC) cows before and after separation, estimated using lactation curve fitting and energy intake data. Red dots indicate CCC cows, and green dots indicate control cows. Cows are labeled according to their group (C = control, T = treatment [CCC]), breed (H = Swedish Holstein, R = Swedish Red), and parity (1–5), plus a running number within each parity (0–10).

into energy in milk (kg milk/MJ ME) was constant for each individual throughout the study period. These assumptions may all have affected the results, and they will be subject to change if future studies reveal that they are inappropriate.

The assumption that milk secretion was constant between milkings may not be valid for long milking intervals. Dutreuil et al. (2016) investigated the effect of milk storage duration in the udder on milk synthesis and found that milk synthesis rate was similar up to 13-h intervals but decreased significantly between 13 and 20 h of milk accumulation. In the current study, cows were not regularly driven to milking, and milking intervals may therefore have been longer than 13 h. However, it can be assumed that CCC cows were suckled between milking occasions, reducing the effects of milk accumulation on milk synthesis rate for them. However, they may have been more affected by inhibited milk secretion due to milk present in the secretory tissue after incomplete milk removal in the milking unit.

Several sources of variation are relevant for our results. After separation, CCC cows may have experienced problems with poor milk ejection, irregular milking intervals, incomplete milkings, or a combination thereof. All these factors could possibly affect milk synthesis in the shorter and longer term (Stelwagen, 2001; Loiselle et al., 2009; Dutreuil et al., 2016; Albaaj et al., 2018). If this was the case, cows would also be estimated to produce less during the prese-

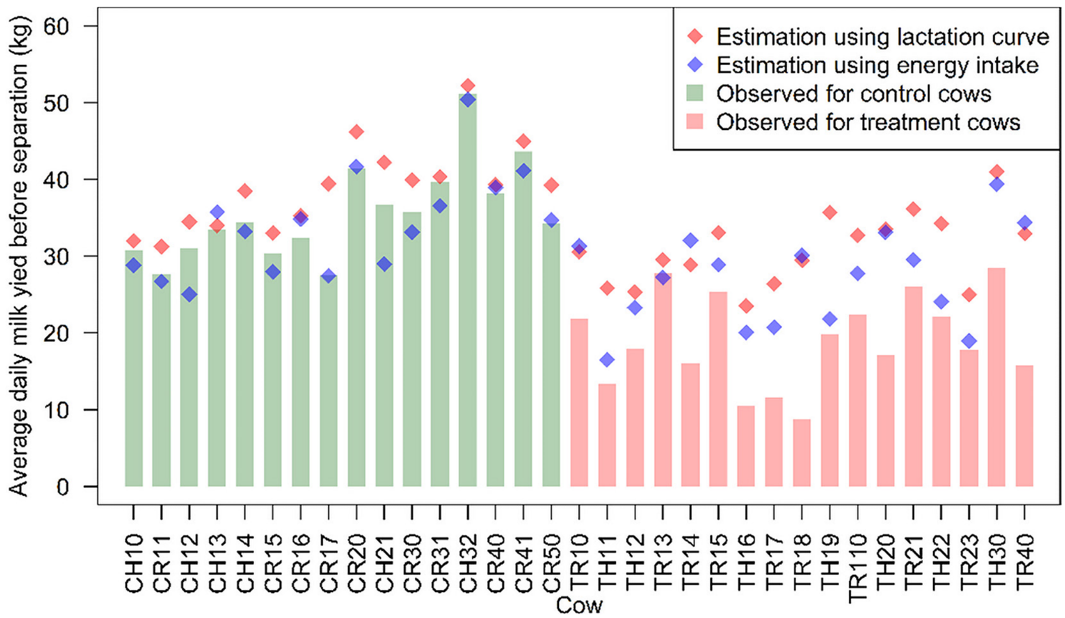

Figure 6. Comparison of average daily milk yield estimates by the 2 methods: The lactation curve method (red diamonds) and the energy intake method (blue diamonds). The lactation curve method was based on the shape of the lactation curve after separation data, while the energy intake method was based on each cow's daily energy intake data and individual ratio between feed intake and milk production. Cows are labeled according to their group (C = control, T = treatment [CCC]), breed (H = Swedish Holstein, R = Swedish Red), and parity (1–5), plus a running number within each parity (0–10).

paration period, as milk yield estimation was based on postseparation data, further accentuating the negative effects of CCC on lactational output. However, management before and immediately after separation may affect occurrence of the aforementioned problems, whereas separation time (in regard to lactation stage) may affect the influence of these problems on production (Stelwagen, 2001).

Estimated milk yield based on lactation curve modeling and energy intake correlated relatively well, indicating a milk yield loss around, respectively, 11 or 7 kg/d before separation. This is in line with the expected calf intake estimated from other studies (de Passillé et al., 2008; Johnsen et al., 2016). However, estimates from the lactation curve method resulted in a slight overestimation of milk yield in control cows (on average by 3.4 kg), indicating that the true milk yield for CCC cows may be even lower than estimated by this method. This can be due to many factors that can affect saleable milk yield and lower it compared with the lactation curve generated by the model, such as cases of subclinical mastitis or social stress at the barn. The estimation based on energy intake showed a slightly larger spread among CCC cows, which may indicate energy partitioning toward body reserves rather than toward milk production. Although not confirmed, CCC cows appeared to have lower decreases in BCS in early lactation compared with control cows (our unpublished data). However, the energy intake method correlated better with actual production among control cows but may be challenging to use in practice, as it requires precision feed intake. For research purposes, we therefore recommend using the energy intake method for estimation of milk yield loss in CCC systems where detailed feed intake measurements are available.

Variation in milking frequency or suckling frequency, or both, can be assumed to be high in our study, and nutrition also affects the amount of milk produced and thereby the shape of the lactation curve. Milking frequency has been found to be the most important factor for determining the milk yield potential, whereas nutrition determines the actual production (Vetharaniam et al., 2003; Nørgaard et al., 2005). A high frequency of milking or suckling in early lactation has been shown to increase milk yield beyond the suckling period (Bar-Peled et al., 1995); however, this effect is dependent on udder emptying, and contrasting results have been found in other studies (Johnsen et al., 2016; Barth, 2020). Very short-term (5 d) incomplete milking combined with nursing the calf has been shown to have positive effects on energy metabolism in early lactation, without any effects on milk yield measured until peak lactation (Carbonneau et al., 2012), whereas Bar-Peled et al. (1998) found that cows that were suckled by calves had more severe negative energy balance compared with cows who were frequently milked.

Disturbed milk ejection is a well-known problem in CCC systems (Johnsen et al., 2016; Zipp et al., 2018), but large variation appears to exist between individual cows (Johnsen et al., 2021). Albaaj et al. (2018) showed that incomplete milk removal has a negative carry-over effect on the subsequent milkings. Their study measured no long-term effect, but in CCC systems it can be theorized that each cow is incompletely milked or suckled several times daily, leading to long-term effects on lactational performance and mammary gland remodeling. Low machine milk yield (high milk loss) in these systems may therefore have one or several causes: disturbed or inexistent milk ejection in the milking unit causing incomplete milk removal and a downregulation of milk synthesis through action of local feedback inhibition mechanisms (Weaver and Hernandez, 2016), or lower udder fill at visits to the milking unit because of a high degree of calf suckling. The current study did not set out to explain the reasons for the lower yield of saleable milk in CCC cows, but these causes should be investigated further.

Calves suckle a substantial amount of the daily production of cows. Scholz et al. (2001) estimated the milk intake of beef suckler calves using 2 different methods: weigh-suckle-weigh and milking using oxytocin injections. They found no significant differences between the methods, but reported that estimated milk intake varied between 6.0 and 29.0 kg, with an average of 16.3 kg. Cows and calves included in the current study were all of dairy breeds, implying a higher production level among cows and possibly a lower intake among calves compared with the Scholz et al. (2001) study. However, variation in intake among calves can still be assumed to be large. In addition, allosuckling was observed during the study, and calves can therefore be assumed to have suckled cows other than their own dams, causing a variation in amount suckled from each cow. The effect of allosuckling on lactational performance needs to be further investigated.

Limitations

The distribution of possible parameter values for lactation curves are far from uniform (Græsbøll et al., 2016). Many factors might affect the shape of the lactation curve (e.g., diets, release to pasture, farm management), so it is crucial to obtain a representative sample to be able to estimate the model parameters for a particular setting. We only had 16 control cows, which was not enough to give reliable estimates of parameter distributions. The estimation of milk yield based on the lactation curve is also sensitive to missing or erroneous milking records, which differed in frequency among cows. The lactation curve estimation also omitted the entire pasture period, due to large variations in milk yield that would have complicated the modeling greatly. Further studies should aim to collect extensive data to model lactation curves for CCC systems. Therefore, we used a GLM to predict the exponential coefficient based on the linear components that can be reliably estimated on data after calf separation. Future studies would benefit from using more sophisticated and accurate models that take into account other cow features, such as breed and parity. We used previous-day energy intake when estimating current day milk yield to account for delays in metabolism (Agenäs et al., 2003). However, different feeds are metabolized at different rates, and the current study did not account for that. Nevertheless, the proposed method showed rather accurate results for control cows. Other limitations influencing our results include the low number of cows in total, the use of 2 different breeds and different parities of cows, movements of animals between different VMS units in the barn, erroneous records from feed troughs, and possible biases related to excluded animals. Although the study included a greater number of Swedish Red than Swedish Holstein cows, the breeds were evenly distributed across the 2 treatments. After separation, cows were kept according to farm routines, which may have included movements to slightly different management: for instance, other cow traffic and AMS models. The feed troughs used in the trial have been known to show erroneous records at times, due to cows stealing feed from each other or faulty sensors. However, troughs were regularly calibrated during the trial to avoid problems. The animals that were excluded from the data set had a larger number of missing records than those retained, most likely related to disease incidences lasting for long periods of time. However unlikely, it cannot be ruled out that these disease incidences may have been related to previous experimental treatments.

Further Research

Further research should aim to replicate the methods proposed here on larger numbers of cows, to investigate the validity of the models. The assumptions made to create the models should also be investigated; that is, that milk secretion rate is constant between milkings and that milk yield reflects energy intake of the previous day in a constant manner on an individual basis. It should also be investigated how including pasture data would affect accuracy of the models.

Milk ejection and loss of saleable milk are well-known difficulties in CCC systems that warrant further investigation. It should be elucidated whether milk yield is actually lower in CCC cows, or whether calf suckling and poor milk ejection together explain the full extent of milk loss. It should also be investigated how timing of separation affects lactation yield, and methods to estimate milk ejection success should be developed.

CONCLUSIONS

We developed 2 models to estimate the loss of saleable milk in a cow-calf contact system with AMS. We found that CCC cows were estimated to produce less than control cows, both before and after calf separation. Modeling milk yield based on the lactation curve slope overestimated production among control cows, indicating that the same may have occurred in CCC cows. Nutrient intake modeling was more accurate in predicting milk yield in control cows but is less practically feasible on farms. We propose that the models should be tested on larger numbers of animals to validate them, and that further research should be conducted on milk yield variations among CCC cows.

ACKNOWLEDGMENTS

We gratefully acknowledge the Beijer Foundation (Uppsala, Sweden), the Swedish Research Council Formas (Stockholm, Sweden; grant number 2018-01500), and the Seydlitz MP Bolagen Foundation (Vetlanda, Sweden) for funding this research. We also thank the staff at the Swedish Livestock Research Centre (Uppsala, Sweden) for their support with conducting the trial. Finally, we thank Coenraad van Zyl (Wageningen University & Research; Wageningen, the Netherlands), who assisted the authors with energy intake estimations. The authors have not stated any conflicts of interest.

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ORCIDS

Mikhail Churakov https://orcid.org/0000-0001-9707-6885
Hanna K. Eriksson https://orcid.org/0000-0003-2424-4707
Sigrid Agenäs https://orcid.org/0000-0002-5118-7691
Sabine Ferneborg https://orcid.org/0000-0002-9218-9407