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Effects of simulated quarter and udder teat cup removal settings on strip milk and milking duration in dairy cows

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ABSTRACT

The aim of this study was to estimate the amount of milk left in quarters and udders and the milking duration for a variety of teat cup removal strategies. A combination of empirical data and simulated quarter and udder teat cup removal settings were used to make these estimates. Milking duration is an important factor in both automatic and conventional milking systems because it directly influences milking efficiency and hence can affect farm profitability. Strategies investigated in the literature to reduce milking duration include the application of different milk flow rate switch-points (milk flow rate at which the milking unit or teat cup is removed). Applying these milk flow rate switch-points can affect the amount of milk that is not harvested (strip milk). We are not aware of previous research analyzing strip milk yield and milking duration at the quarter level, across a range of quarter and udder milk flow rate switch-points. Quarter-level average milking duration decreased by 2 min, and strip milk increased 1.3 kg as quarter milk flow rate switch-point was increased from 0.2 kg/min to 1.0 kg/min. Using an end of milking criterion of removal of the teat cup at 50% of the quarter's rolling average milk flow rate resulted in a 0.4-min reduction in milking duration and a 0.08-kg increase in strip milk per quarter, compared with removal of the teat cup at 30% of the quarter's rolling average milk flow rate. Udder-level average milking duration decreased by 1.4 min, and strip milk increased by 0.76 kg (0.19 kg per quarter) as udder milk flow rate switch-point was increased from 0.2 kg/min to 1.0 kg/min. A 0.8-min reduction in cow milking duration and a 0.27-kg increase in strip milk at the udder level (0.08 kg per quarter) resulted when changing udder milk flow rate switch-point from 30% of the udder rolling average to 50% of the udder rolling average milk flow rate. This study provides quantitative estimates of the effect of teat cup milk flow rate switch-points on milking duration and strip milk yield.

Key words: teat cup removal setting, strip milk, milking duration, milking efficiency

INTRODUCTION

The increase seen in milk yield per cow over the past decades has contributed to increased milking duration; however, longer milkings do not always result in greater milk yield. The duration of milking is an important consideration in dairy farming for both conventional and automatic milking systems (**AMS**). In conventional milking systems, the need to minimize production costs and the difficulties of finding skilled labor make the milking process a challenging activity (Jago et al., 2010), especially because milking is the most labor-intensive task on dairy farms, accounting for 33% of overall labor demand (Deming et al., 2018). In AMS, key factors driving efficiency and productivity are milking duration and total time spent milking per day in the robot (Gygax et al., 2007). Morveover, Castro et al. (2012) found that one of the most important factors determining milk yield per AMS and per year was average milk flow rate, which was inversely associated with milking duration.

The desire for shorter milkings has driven research on teat cup removal settings. At the udder level, Edwards et al. (2013) saw a reduction in milking duration of 18% when the cluster milk flow rate switch-point (milk flow rate at which the cluster is removed) increased from 0.2 kg/min to 0.8 kg/min at the udder level. Also, Burke and Jago (2011) found that milking duration was reduced by 11% by increasing the cluster milk flow rate switch-point from 0.2 kg/min to 0.4 kg/min at the udder level. In high-producing dairy cows, Stewart et al. (2002) found a 10- to 15-s reduction in milking duration by increasing the milk flow rate switch-point from 0.73 kg/min to 0.82 kg/min at the udder level. At the quarter level, Ipema and Hogewerf (2002) found a 10% reduction in milking duration when quarter milk

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flow rate switch-point was increased from 0.05 to 0.15 kg/min, and Krawczel et al. (2017) found that milking duration was 0.9 min (12%) shorter when the teat cup milk flow rate switch-point was increased from 0.06 kg/min to 0.48 kg/min at the quarter level.

Increasing the milk flow rate switch-point can result in variable amounts of unharvested milk, which could result in a reduction in milk production and negative effects on udder health and milk quality, although the degree of undermilking at which these effects might occur is not well known. The influence of milk remaining in the gland on reducing milk secretion is thought to be due to the accumulation of substances that modulate milk secretion when in contact with epithelial cells (Henderson and Peaker, 1987; Weaver and Hernandez, 2016). The influence and causal effect of milk remaining in the gland on SCC is less clear. A study by Penry et al. (2017) found a slight increase in SCC from 26,300 to 48,300 cells/mL and a 25% reduction in milk production rate when approximately 30% of the milk was left in a half udder when cows were milked twice per day. A subsequent study by Kuehnl et al. (2019) showed that regardless of whether half udders were milked 2 or 3 times per day, they had 27% lower milk production and SCC increased by 25,700 cells/mL compared with half udders milked completely. However, Rasmussen (1993) found no differences in clinical or subclinical mastitis when comparing a cluster switch-point of 0.2 kg/min with 0.4 kg/min applied at the udder level. Moreover, Burke and Jago (2011) found that changing cluster milk flow rate switch-point from 0.2 kg/min to 0.4 kg/min at the udder level did not negatively affect SCC; however, a small (1%) but statistically significant drop in milk yield was observed. Additionally, Clarke et al. (2008) reported that removing the clusters at 0.8 kg/min, compared with 0.3 kg/min at the udder level, did not cause an increase in SCC for either infected or uninfected quarters. In an AMS, Krawczel et al. (2017) saw no effect on SCC or milk yield when teat cup milk flow rate switch-point was increased from 0.06 kg/min to 0.48 kg/min at the quarter level. The study by Penry et al. (2017) measured the milk left in the quarter, and thus it is not comparable with a specific milk flow rate switch-point used in other studies. As a reference, the studies by Edwards et al. (2013) and Clarke et al. (2008) reported increases in strip milk of approximately 0.3 L at the udder level when increasing the milk flow rate switch-point up to 0.8 kg/min. It seems clear that the effect of undermilking on milk yield and the potential effect on SCC is volume-dependent and that the relationship between milk left in the gland and its effect on milk production and milk quality is not entirely understood.

It is important to understand how milk left in the quarter and milking duration are affected when different milk flow rate switch-points at the quarter and udder level are used. Our hypothesis was that increasing the milk flow rate switch-point would reduce milking duration and increase strip milk. Therefore, the objective of this study was to quantify the effects of different simulated teat cup milk flow rate switch-points applied at the quarter and udder level on milking duration and the amount of milk left in the quarters and udders.

MATERIALS AND METHODS

Cow Selection

We used 17 Holstein Friesian cows from the Dairy Cattle Center herd from the University of Wisconsin-Madison. Cows were housed in individual tiestalls with bedded mattresses and were fed a TMR diet. These animals were part of an 84 milking-cow herd, averaging approximately 40 kg/cow per day, that were milked twice a day (at 0400 and 1600 h) at the udder level in a herringbone parlor. Cows used in this study were selected to have a wide range of lactations (mean 2.5, SD 1.7, range 1 to 7) and DIM (mean 240, SD 100, range 99 to 418). The average udder milk yield per milking for the experimental cows was 14 kg (SD 3.1, range 9.8 to 19) with an average quarter milk yield of 3.6 kg (SD 0.9, range 1.6 to 5.9).

Milking

Seven cows were milked once on one day, and a power study was done with these data to estimate the number of cows and quarters needed to achieve a detectable difference of less than 1% in quarter-level milk yield and milking duration. Based on these calculations a second group of 10 cows were milked once on a subsequent day.

Cows were completely milked using a novel quarter milking device (Mi4, Upton et al., 2016), using a vacuum level of 43 kPa, 65:35 pulsator ratio, and pulsation rate of 60 cycles per minute. The experimental cows were milked before the afternoon milking with a resulting milking interval that ranged from 8 to 11 h. Cumulative quarter-level milk weights were recorded throughout the milking at a frequency of 1,000 HZ. The milking routine consisted of pre-stripping for detection of clinical mastitis, followed by pre-dipping and cleaning of the quarters before attachment of the teat cups. Machine stripping was applied when observation of the milking unit indicated that no milk was being extracted, to ensure that all milk was removed from each quarter. The total amount of milk extracted during the milking (including machine stripping) was taken as the total milk yield at the quarter or udder level.

Data Management

Milk flow rates (kg/min) were determined by linear regression of milk weight versus time in 5-s increments. Peak milk flow rate (**PMF**, kg/min) was calculated as the maximum 30-s rolling average milk flow rate (an average of six 5-s milk flow rate measurements).

Algorithms were developed in SAS (v. 9.4, fourth ed., SAS Institute Inc., Cary, NC) to determine the milking duration (**MD**, min) from teat cup attachment to simulated teat cup removal and amount of milk harvested up to the simulated teat cup removal for different removal strategies. Strip milk weight (**SM**, kg) was calculated as the total milk yield (including machine stripping) minus the milk harvested up to the point of simulated teat cup removal. Additionally, the slowest-milking quarter within an udder was identified for each milk flow rate switch-point and MD was calculated. For the udder-level analysis, information from the 4 quarters of a cow was aggregated, and quarter SM, udder SM, and cow MD were calculated. Average milk flow rate (**AMF**, kg/min) was calculated as kilograms of milk harvested from teat cup attachment to simulated teat cup removal, divided by the simulated milking duration.

Five removal strategies used the 5-s-interval absolute milk flow rate as the switch-point criterion for teat cup removal at the quarter and udder level: 0.2 kg/min (**MFR0.2**), 0.4 kg/min (**MFR0.4**), 0.6 kg/min (**MFR0.6**), 0.8 kg/min (**MFR0.8**), and 1.0 kg/min (**MFR1.0**). Two strategies used a percentage of the 30-s rolling average milk flow rate as the criterion for teat cup removal at the quarter and udder level: 30% (**RAMF30**) or 50% (**RAMF50**). The subscripts $_{\mathbf{Q}}$ and $_{\mathbf{U}}$ are used to identify whether the treatment or response is measured at quarter or udder level (e.g., $\mathbf{MD_Q}$ and $\mathbf{MD_U}$ for quarter and udder milking duration, respectively).

One quarter registered a milk flow rate of zero during the majority of the milking and was removed from the quarter analysis because the milk flow rate switch-point was not applicable for such a low flow rate. For the quarter-level percentage-based switch-points, 3 quarters never reached the milk flow rate switch-point for either removal level and were removed from the quarter analysis for the $\mathrm{RAMF30_Q}$ and $\mathrm{RAMF50_Q}$ treatments. One cow did not reach the udder-level percentage-based milk flow rate switch-point and was removed from the udder analysis for the $\mathrm{RAMF30_U}$ and $\mathrm{RAMF50_U}$ treatments.

Statistical Analysis

We used a mixed model procedure (Proc Mixed, SAS 9.4). Model selection was conducted by offering all possible explanatory variables to the model using a backward selection method, and the final model was selected based on the lowest Akaike information criterion value. Treatment (MFR0.2, MFR0.4, MFR0.6, MFR0.8, and MFR1.0, or RAMF30 and RAMF50) and cow were declared as class variables. We classified SM, MD, PMF, and milk yield as continuous variables. Treatment and PMF were classified as fixed effects. Cow was declared as a random variable. A repeated measures statement was included in the model to address the repeated data from quarters within cow. Additionally, to account for repeated measures at the quarter level, a compound symmetry error structure was used. The effects of the day a cow was milked, lactation number, and DIM were not significant.

The final model for MD for the slowest quarter and for SM and MD for the quarter and whole udder was

$$y = Treatment + MilkYield + PMF, \quad [1]$$

where y represented the following dependent variables: $\mathrm{SM_Q}$, $\mathrm{SM_U}$ [strip milk weight (kg)], the weight of milk left after teat cup or cluster removal at the quarter and udder levels, respectively; $\mathrm{MD_Q}$, $\mathbf{MD_{SQ}}$, and $\mathrm{MD_U}$ [milking duration (min)], time from cluster or teat cup attachment to cluster or teat cup detachment at the quarter, slowest quarter, and udder levels, respectively.

For treatments applied at the udder level, the outcomes and covariates were all taken as udder-level statistics. Descriptive statistics were also calculated at the quarter level for these udder-level treatements. Quarters were ranked according to their within-udder milking duration, with the fastest quarter having the shortest milking duration and the slowest quarter the longest milking duration. Overmilking duration of each quarter was determined by the elapsed time from when that quarter had a milk flow rate less than 0.2 kg/min to when the udder reached the switch-point (Figure 1). The SM was also calculated at the quarter level for these within-udder rankings (Figure 2).

RESULTS

Milking Duration

Absolute Milk Flow Rate Switch-Point. For treatments applied at the quarter level, $\mathrm{MD_Q}$ decreased by 2.0 min as the switch-point increased from $\mathrm{MFR0.2_Q}$ to $\mathrm{MFR1.0_Q}$ ($P < 0.001$; Table 1). Milk yield was strongly associated with MD_Q ($P < 0.0001$) with each kilogram increase in milk yield increasing MD_Q by 0.7 min (data not shown). We also found a negative association between MD_Q and quarter-level PMF ($P < 0.0001$) with each 1.0-kg/min increase in PMF, resulting in a 1.1-min reduction in MD_Q. The slowest quarter had a 2.2-min decrease in MD_{SQ} ($P < 0.001$) as the switch-point increased (Table 1).

Treatments applied at the udder level resulted in MD_U decreasing by 1.4 min ($P < 0.001$) as the switch-point increased from $MFR0.2_U$ to $MFR1.0_U$ (Table 2). Descriptive statistics for quarter-level overmilking time (defined as quarter milk flow rate <0.2 kg/min) are shown in Figure 1. Both udder milk yield and PMF were highly associated with MD_U ($P < 0.0001$), with each 1.0-kg increase in milk yield and PMF resulting in 0.3-min longer and 0.8-min shorter MD_U respectively.

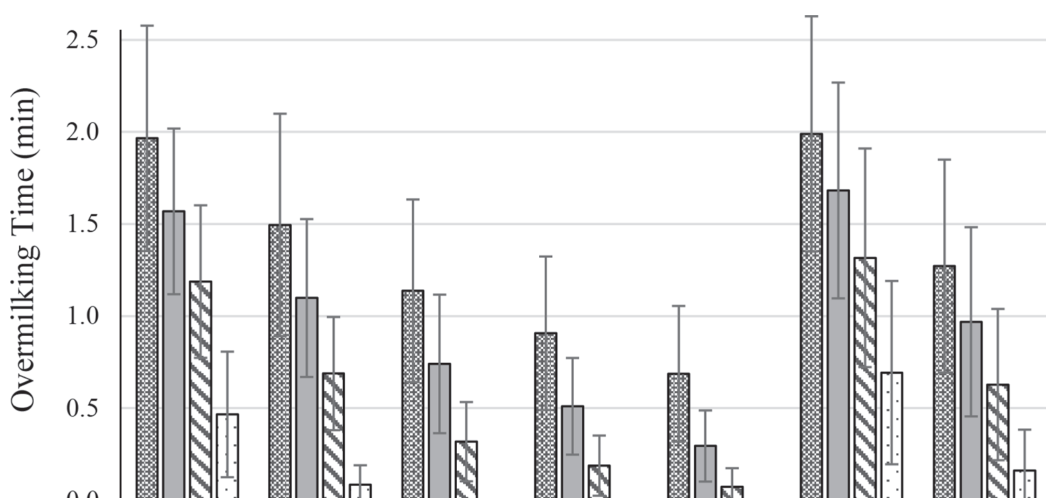
Percentage-Based Switch-Point. For the quarter-level treatments, MD_Q was 0.4 min shorter ($P < 0.001$) for $RAMF50_Q$ than for $RAMF30_Q$ (Table 1). For the slowest quarter, MD_{SQ} was 0.5 min shorter ($P = 0.0006$) for $RAMF50_Q$ than for $RAMF30_Q$ (Table 1). The estimated teat cup removal milk flow rate for the $RAMF50_Q$ setting was 0.17 kg/min and 0.06 kg/min for the $RAMF30_Q$ setting at the quarter level.

For udder-level treatments, MD_U was 0.8 min shorter ($P = 0.01$) for $RAMF50_U$ than for $RAMF30_U$. The absolute milk flow rate at simulated cluster removal averaged 0.14 kg/min for the $RAMF30_U$ treatment and 0.45 kg/min for the $RAMF50_U$ treatment. Quarter overmilking times, with udder milk flow rate switch-points, are shown in Figure 1.

Strip Milk

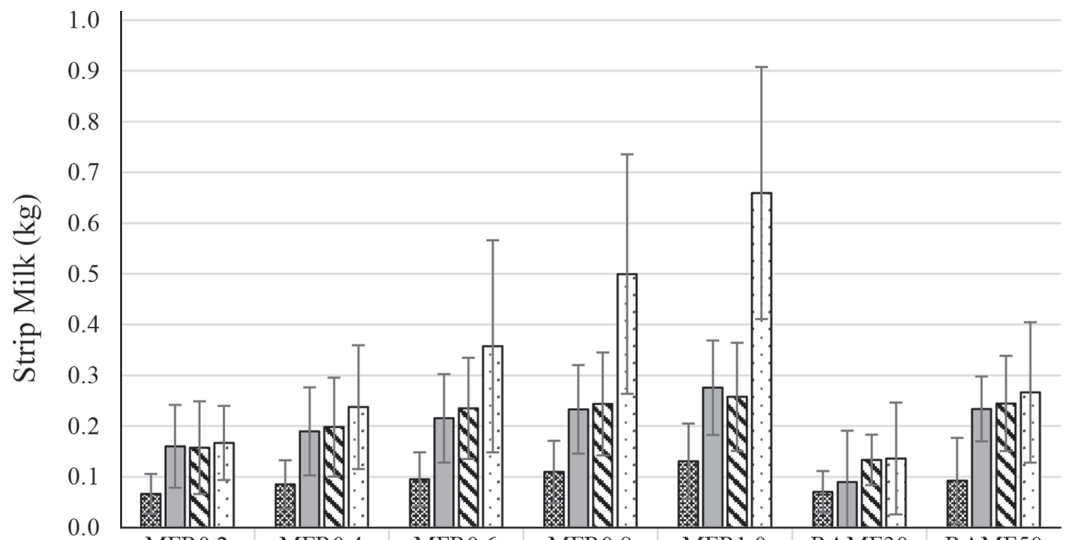
Absolute Milk Flow Rate Switch-Point. For quarter-level treatments SM_Q increased by 1.3 kg ($P < 0.001$) from $MFR0.2_Q$ to $MFR1.0_Q$ (Table 1). Both quarter PMF and milk yield were associated ($P < 0.0001$) with SM_Q, decreasing by 1.0 kg for each kilogram-per-minute increase in quarter PMF and increasing by 0.3 kg per kilogram increase in milk yield. Treatments applied at the udder level also resulted in an increase of 0.76 kg in SM_U ($P < 0.001$) from $MFR0.2_U$ to $MFR1.0_U$ (Table 2). Descriptive statistics for SM at the quarter level with the udder level milk flow rate switch-points are presented in Figure 2.

Percentage-Based Switch-Point. For quarter-level treatments, SM_Q was 0.08 kg greater for $RAMF50_Q$ than for $RAMF30_Q$ ($P = 0.02$) (Table 1), whereas for



	MFR0.2	MFR0.4	MFR0.6	MFR0.8	MFR1.0	RAMF30	RAMF50
Fastest	1.97	1.50	1.14	0.91	0.69	1.99	1.27
Second	1.57	1.10	0.74	0.51	0.29	1.68	0.97
Third	1.19	0.69	0.32	0.19	0.07	1.32	0.63
Slowest	0.47	0.08	0.00	0.00	0.00	0.69	0.16

Figure 1. Quarter overmilking duration with udder milk flow rate switch-points ranked according to within-udder milking duration. Fastest = quarter with the shortest milking duration in the udder; second = quarter with the second-shortest milking duration in the udder; third = quarter with the third-shortest milking duration in the udder; slowest = quarter with the longest milking duration in the udder. MFR0.2 = simulated cluster milk flow switch-point at 0.2 kg/min; MFR0.4 = simulated cluster milk flow switch-point at 0.4 kg/min; MFR0.6 = simulated cluster milk flow switch-point at 0.6 kg/min; MFR0.8 = simulated cluster milk flow switch-point at 0.8 kg/min; MFR1.0 = simulated cluster milk flow switch-point at 1.0 kg/min; RAMF30 = simulated cluster milk flow switch-point at 30% of the average flow rate; RAMF50 = simulated cluster milk flow switch-point at 50% of the average flow rate. Error bars represent SD.



	MFR0.2	MFR0.4	MFR0.6	MFR0.8	MFR1.0	RAMF30	RAMF50
Fastest	0.07	0.08	0.10	0.11	0.13	0.07	0.09
Second	0.16	0.19	0.22	0.23	0.28	0.09	0.23
Third	0.16	0.20	0.23	0.24	0.26	0.13	0.24
Slowest	0.17	0.24	0.36	0.50	0.66	0.14	0.27

Figure 2. Quarter strip milk with udder milk flow rate switch-points ranked according to within-udder milking duration. Fastest = quarter with the shortest milking duration in the udder; second = quarter with the second-shortest milking duration in the udder; third = quarter with the third-shortest milking duration in the udder; slowest = quarter with the longest milking duration in the udder. MFR0.2 = simulated cluster milk flow switch-point at 0.2 kg/min; MFR0.4 = simulated cluster milk flow switch-point at 0.4 kg/min; MFR0.6 = simulated cluster milk flow switch-point at 0.6 kg/min; MFR0.8 = simulated cluster milk flow switch-point at 0.8 kg/min; MFR1.0 = simulated cluster milk flow switch-point at 1.0 kg/min; RAMF30 = simulated cluster milk flow switch-point at 30% of the average flow rate; RAMF50 = simulated cluster milk flow switch-point at 50% of the average flow rate. Error bars represent SD.

treatments applied at the udder level, SM_Q was 0.07 kg and SM_U was 0.27 kg greater for $RAMF50_U$ than for $RAMF30_U$ ($P < 0.001$ and $P = 0.02$ for SM_Q and SM_U, respectively; Table 2). Neither SM_Q nor SM_U were associated with milk yield or PMF for the percentage-based treatments at the quarter or udder level.

At the quarter level, we found weak evidence ($P = 0.04$) that AMF was affected by the treatment, with only the $MFR0.2_Q$ having a lower AMF than the other treatments. The percentage reduction in MD and milk yield were similar, resulting in little change in AMF. At the udder level a significant increase in AMF ($P <$

Table 1. Results of teat cup removal strategies applied at the quarter level

	Simulated treatment[1]										
Item	$MFR0.2_Q$	$MFR0.4_Q$	$MFR0.6_Q$	$MFR0.8_Q$	$MFR1.0_Q$	SEM	*P*-value	$RAMF30_Q$	$RAMF50_Q$	SEM	*P*-value
Quarter strip milk [kg (%)]	0.2^a (7.3)	0.4^a (13.0)	0.8^b (23.6)	1.2^c (34.1)	1.5^d (42.3)	0.08	<0.001	0.20^a (5.6)	0.28^b (8.1)	0.04	0.02
Quarter milking duration (min)	4.4^a	4.0^b	3.3^c	2.7^d	2.4^e	0.11	<0.001	4.7^a	4.3^b	0.12	<0.001
Slowest quarter milking duration (min)	5.2^a	4.8^{ab}	4.4^b	3.3^c	3.0^c	0.22	<0.001	5.8^a	5.3^b	0.22	<0.001

[a–e]Different letters within a parameter indicate significant differences between the treatments at the $\alpha = 0.05$ level.

[1]LSM for the simulated treatments. $MFR0.2_Q$ = simulated teat cup milk flow switch-point at 0.2 kg/min; $MFR0.4_Q$ = simulated teat cup milk flow switch-point at 0.4 kg/min; $MFR0.6_Q$ = simulated teat cup milk flow switch-point at 0.6 kg/min; $MFR0.8_Q$ = simulated teat cup milk flow switch-point at 0.8 kg/min; $MFR1.0_Q$ = simulated teat cup milk flow switch-point at 1.0 kg/min; $RAMF30_Q$ = simulated teat cup milk flow switch-point at 30% of the average flow rate; $RAMF50_Q$ = simulated teat cup milk flow switch-point at 50% of the average flow rate. Values in parentheses represent strip milk as a percentage the total milk available for harvesting.

0.05) occurred as milk flow rate switch-point increased (data not shown).

DISCUSSION

As the simulated milk flow rate switch-point was increased at both the quarter and udder level, we saw a steady decrease in MD and a steady increase in SM at the quarter and udder levels. There are clear advantages to reducing MD to improve the labor and capital efficiency of milk harvesting. These are balanced against the potential negative effects of increased SM: primarily reduced milk production and, secondarily, changes in milk components and other aspects of milk quality. This study was undertaken to gain a better understanding of the effects of teat cup removal strategies on both MD and SM.

The 1.1-min (19%) reduction in MD_U between our $MFR0.2_U$ and $MFR0.8_U$ treatments was comparable to the 1.3-min (18%) reduction found by Edwards et al. (2013). The MD_U reduction of 0.5 min (9%) between our $MFR0.2_U$ and $MFR0.4_U$ treatments was also consistent with Jago et al. (2010), who reported a 0.7-min (11%) reduction in MD_U in mid- to late-lactation cows with the same milk flow rate switch-point increase, a smaller reduction compared with early-lactation cows. Edwards et al. (2014) reported a shorter decline phase in mid- to late-lactation, which helps explain this smaller effect. Besier and Bruckmaier (2016) reported that simulated MD was reduced by 1.3 min (or 19%) for a constant vacuum treatment when the udder-level milk flow rate switch-point was increased from 0.2 kg/min to 1.0 kg/min. This reduction compares well with our result of a 1.4-min reduction in MD_U but with a somewhat greater percentage reduction (25%). Our average milk yield per milking was slightly less (14 kg vs. 15.4 kg) and our AMF and PMF were higher (2.5 kg/min vs. 1.89 kg/min for AMF, and 4.2 vs. 3.27 kg/min for PMF), resulting in shorter milking duration (5.7 min vs. 6.7 min for the $MFR0.2_U$ treatment) than the study by Besier and Bruckmaier (2016), explaining our larger percentage reduction in MD.

When milk flow rate switch-points were applied at the quarter level, our predicted reduction in MD_Q (2.0 min from $MFR0.2_Q$ to $MFR1.0_Q$) was considerably larger than the reduction in MD_U for the same switch-point applied at the udder level (1.4 min from $MFR0.2_Q$ to $MFR1.0_Q$). A study by Krawczel et al. (2017) reported a 0.9-min (12%) reduction in MD between 0.06 kg/min and 0.48 kg/min switch-point settings. Although the switch-point settings used in our study were not the same as those used by Krawczel et al. (2017), the reduction in MD was comparable: 0.4-min (9%) reduction in MD_Q between $MFR0.2_Q$ and $MFR0.4_Q$, and 1.1-min (25%) reduction between $MFR0.2_Q$ and $MFR0.6_Q$.

For treatments applied at the udder level, considerable within-udder differences in overmilking duration occurred for individual quarters (Figure 1). Overmilking is an undesirable condition because it leads to unnecessary extension of the milking and can lead to deterioration of teat end condition (Hillerton et al., 2002). A study by Sandrucci et al. (2007) reported an udder overmilking duration of 0.8 min, corresponding to 12.8% of the milking time. Our study showed a large variation between the quarters within an udder. The average overmilking duration for the fastest quarter of each udder was reduced by 1.28 min across the udder-level MFR treatments, whereas average overmilking duration of the slowest milking quarter of each udder was reduced by 0.47 min (Figure 1). This indicates that when the udder reaches the milk flow rate switch-point, most of the milk has been removed in several quarters, which also explains the differences in SM with the switch-points applied at the quarter and udder levels. Moreover, when we analyzed the MD of the slowest milking quarter, we found that MD_{SQ} approached MD_Q for the highest switch-points applied at the quarter level and approached MD_U for the lowest switch-points

Table 2. Results of teat cup removal strategies applied at the udder level

Item	Simulated treatment[1]										
	$MFR0.2_U$	$MFR0.4_U$	$MFR0.6_U$	$MFR0.8_U$	$MFR1.0_U$	SEM	*P*-value	$RAMF30_U$	$RAMF50_U$	SEM	*P*-value
Udder strip milk, [kg (%)]	0.54[a] (3.8)	0.70[a] (5.0)	0.89[b] (6.4)	1.07[b] (7.6)	1.30[c] (9.4)	0.12	<0.001	0.55[a] (4.0)	0.82[b] (6.0)	0.11	0.02
Udder milking duration (min)	5.7[a]	5.2[b]	4.8[c]	4.6[cd]	4.3[d]	0.19	<0.001	5.7[a]	4.9[b]	0.29	0.01

[a–d]Different letters within a parameter indicate significant differences between the treatments at the $\alpha = 0.05$ level.

[1]LSM for the simulated treatments. $MFR0.2_U$ = simulated cluster milk flow switch-point at 0.2 kg/min; $MFR0.4_U$ = simulated cluster milk flow switch-point at 0.4 kg/min; $MFR0.6_U$ = simulated cluster milk flow switch-point at 0.6 kg/min; $MFR0.8_U$ = simulated cluster milk flow switch-point at 0.8 kg/min; $MFR1.0_U$ = simulated cluster milk flow switch-point at 1.0 kg/min; $RAMF30_U$ = simulated cluster milk flow switch-point at 30% of the average flow rate; $RAMF50_U$ = simulated cluster milk flow switch-point at 50% of the average flow rate. Values in parentheses represent strip milk as a percentage the total milk available for harvesting.

applied at the udder level. This finding, combined with the overmilking results, where the 3 fastest quarters are being overmilked for a substantial period of time for switch-points below 0.6 kg/min, suggest that the slowest quarter is the main determinant of MD_U when those switch-points are used. Additionally, considering the excessive time some quarters are being milked with a very low milk flow, or with no milk flow, further strategies for optimal quarter milkability while achieving minimal overmilking could be explored for conventional milking systems.

Our results for strip milk were also in general agreement with other studies. Jago et al. (2010) and Edwards et al. (2013) found no difference in SM_U between the $MFR0.2_U$ and the $MFR0.4_U$ treatments, in agreement with our result. Burke and Jago (2011) did, however, report a small difference in SM_U between $MFR0.2_U$ and the $MFR0.4_U$ treatments (0.19 kg vs. 0.35 kg, respectively, which represented 1.9% and 3.4% of the total milk yield). Besier and Bruckmaier (2016) estimated that a simulated 1.0 kg/min switch-point applied at the udder level resulted in SM of 6.9% of the total milk yield. Given their udder level milk yield of 15.8 kg, this would result in a SM of about 1.1 kg, which was close to our result of 1.3 kg or 9.4% of total udder milk yield for our $MFR1.0_U$ treatment.

Analysis revealed differences of up to 1.3 kg in SM_Q between treatments applied at the quarter level in this study. We are not aware of literature reporting the effect of switch-point on SM at the quarter level. Additionally, we found considerably more SM_Q for treatments applied at the quarter level (42% of the quarter milk yield) than SM_Q for treatments applied at the udder level (9.4% of the quarter milk yield), and this increased as the milk flow rate switch-point was increased. For $MFR0.2_Q$, the estimate for SM_Q was 0.2 kg, whereas for $MFR0.2_U$ the SM_Q ranged from 0.07 kg to 0.17 kg. When the switch-point was increased to 1 kg/min, the $MFR1.0_Q$ treatment resulted in SM_Q of 1.5 kg, and $MFR1.0_U$ resulted in a range of SM_Q from 0.13 kg to 0.66 kg. This is due to the differences in milk flow rate characteristics at the udder and quarter levels. Weiss et al. (2004) reported that the end of the plateau phase in a quarter was related to the milk available in that quarter, whereas the end of the plateau phase at the udder level was determined by the duration of this phase in the fastest milking quarter. Tančin et al. (2007) also reported that at the udder level, the decline phase begins when the first quarter begins its decline phase and continues in a stepwise order until the slowest milking quarter completes this phase, resulting in different degrees of emptiness of the quarters when the udder-level switch-point is used. This pattern is also apparent in the average quarter-level overmilking durations (Figure 1). For the $MFR0.2_U$ treatment the fastest milking quarter had an overmilking time of almost 2 min and steps down by increments of about 0.5 min for the second-fastest, third-fastest, and slowest quarters occurred as a result of the sequential emptying of quarters.

We found large within-udder variability in SM_Q that increased as the udder-level switch-point was increased (Figure 2). For the lowest switch-point ($MFR2.0_U$), we discovered little difference in SM between quarters, but at the highest switch-point ($MFR1.0_U$), the average SM of the slowest quarter was about 5 times greater than that of the fastest milking quarter.

To our knowledge, no previous studies have simulated a percentage-based milk flow rate switch-point at the udder or quarter level and their effect on MD or quarter SM. This switch-point strategy is used at the quarter level by some AMS. Our analysis also included application of this strategy at the udder level. In our study, the reduction in MD_U was similar to the 0.7-min difference, or a 12% reduction, between the 0.2-kg/min and 0.4-kg/min removal settings reported in the Edwards et al. (2013) study. The estimated absolute milk flow rate at teat cup removal for the $RAMF50_Q$ switch-point was 0.17 kg/min and 0.06 kg/min for the $RAMF30_Q$ switch-point at the quarter level, and were lower than the flow rates deployed in any of the absolute flow rate switch-points studied, which may explain the lower reduction of MD between the treatments. In our study the percentage-based milk flow rate switch-point resulted in SM and MD similar to the lowest absolute flow rate switch-point strategies. Use of a 30-s rolling average comparison for determination of the switch-point results in less reduction of MD for cows or quarters that have a prolonged decline phase.

Although this study was not designed to test the effect of SM on milk production, our results can help in the interpretation of previous studies and in the design of new studies to explore this relationship. Krawczel et al. (2017) found no differences in daily milk yield between 0.06-, 0.3-, and 0.48-kg/min switch-points applied at the quarter level but did not measure SM. Our study suggests that the SM_Q for these treatments would have been on the order of 0.1 kg, 0.3 kg, and 0.6 kg, respectively. Penry et al. (2017) and Kuehnl et al. (2019) reported significantly lower milk production rates when early-lactation cows were severely undermilked, leaving about 1.4 kg of SM in a quarter. Our study suggests that $MFR1.0_Q$ would produce a similar SM_Q. Burke and Jago (2011) reported a 1% lower milk yield for a 0.4-kg/min udder-level switch-point than for a 0.2-kg/min udder-level switch-point in a long-term study. They attributed this difference to the proportion of cows having a strip yield higher than 0.5 L at the udder level. The slowest milking quarters for our $MRF0.2_U$ treatment averaged 0.17 kg SM_Q, and the slowest milking quarters for our $MFR0.4_U$ treatment averaged 0.24 kg SM_Q. Edwards et al. (2013) found no differences in milk yield between a 0.2-kg/min and a 0.8-kg/min switch-point even though significant differences in SM_U occurred between the 2 treatments (0.27 kg vs. 0.57 kg), which is in contradiction to the Burke and Jago (2011) study and not explained by our results. For the $MFR0.8_U$ switch-point Edwards et al. (2013) reported lower SM_U (0.57 kg vs. 1.1 kg) and higher MD (6.0 min vs. 4.6 min) than our study for similar milk yield per milking (14.9 kg vs. 14 kg). The differences in MD and SM may be due to differences in the milk flow rate characteristics of cows or to differences in the way that the 0.8-kg/min switch-point criteria was calculated and applied by the commercial milk meter used in the Edwards et al. (2013) study.

We found that PMF was negativley associated with both SM_Q and SM_U for MFR treatements, but PMF was not associated with SM_Q or SM_U for the percentage-based milk flow rate switch-points. These results are partially in contrast with Weiss et al. (2004), who did not find a correlation between PMF and SM at either quarter or udder level, although they did find a negative correlation between SM and the duration of the plateau phase at the quarter level and negative correlation between the durations of the plateau and decline phases at the quarter level but not at the udder level. Our calculation of PMF was the maximum 30-s rolling average milk flow rate, whereas the PMF used by Weiss et al. (2004) was averaged over the entire plateau phase of milking, which could be several minutes in duration. Our calculation method likely resulted in higher PMF values than did the method used by Weiss et al. (2004). We also did not take into account any effects related to the duration of the decline phase or the shape of the milk flow curve, which were shown by Weiss et al. (2004) to influence SM.

CONCLUSIONS

Increasing the simulated milk flow rate switch-point from 0.2 kg/min to 1.0 kg/min at the quarter level reduced MD_Q by 2.0 min (45%) and, at the udder level, reduced MD_U by 1.4 min (25%). The same treatments resulted in an increase in SM_Q from 0.2 kg to 1.5 kg and an increase in SM_U from 0.56 kg to 1.3 kg. Increasing the simulated percentage-based switch-point from 30% of the rolling average milk flow rate to 50% of the rolling average flow rate at the quarter level reduced MD_Q by 0.4 min (9%) and, at the udder level, reduced MD_U by 0.8 min (14%). With the same increase in percentage-based switch-points, SM_Q increased from 0.20 kg to 0.28 kg, and SM_U increased from 0.56 to 0.84 kg. Teat cup removal settings applied at the udder level produced considerably more within-udder variation in overmilking and SM_Q than did application at the quarter level. The results of this study can be used to aid in interpretation of previous studies on teat cup removal strategies in which MD_Q, SM_Q, or SM_U were not measured and to aid in the design of new experiments to gain better understanding of how teat cup removal settings affect SM, milk yield, and milk quality.

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