Milk flow-dependent vacuum loss in high-line milking systems: Effects on milking characteristics and teat tissue condition

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ABSTRACT

To study the effects of a milking system that partially compensates for milk flow-dependent vacuum loss compared with a standard (high-line) milking unit in a tie-stall barn, milk flow and vacuum patterns were recorded in 10 cows during machine milking with 2 milking systems in a crossover design for 7 d each. Before and after each treatment period postmilking teat condition was recorded by ultrasound cross-sectioning. Additionally, 2 methods to measure teat tissue condition were compared: longitudinal teat ultrasound cross-sectioning and teat tissue density measurements with the spring-loaded caliper (cutimeter method). The partial compensation of milk flow-dependent vacuum loss caused an elevation of the peak flow rate (4.74 ± 0.08 vs. 4.29 ± 0.07 kg/min) and a shorter duration of plateau (1.57 ± 0.06 vs. 1.96 ± 0.07 min) compared with the standard milking system. Total milk yield, duration of incline and decline of milk flow, average milk flow, time until peak flow rate, main milking time, and total milking time did not differ between treatments (overall means: 13.75 ± 0.17 kg; 0.65 ± 0.01 min; 2.88 ± 0.09 min; 2.82 ± 0.05 kg/min; 1.65 ± 0.03 min; 5.23 ± 0.09 min, and 5.30 ± 0.10 min, respectively). The vacuum drop in the short milk tube during periods of high milk flow was less in the compensating vacuum than in the standard milking system (11 ± 1.1 vs. 15 ± 0.7 kPa). Teat measures as determined by ultrasound remained unchanged over the entire experimental period with both milking systems. Postmilking teat tissue measures including their recovery within 20 min after the end of milking show a correlation (0.85 and 0.71, respectively) between the methods used (ultrasound and cutimeter method). In conclusion, a more constant vacuum at the teat tip (within the short milk tube) during periods of high milk flow affected milk flow patterns, mainly increasing peak flow rate. However, the reduced vacuum loss did not increase the overall speed of milking. In

addition, effects of higher vacuum stability on teat condition and udder health were not obvious.

Key words: vacuum loss, high-line milking unit, milk flow, udder health

INTRODUCTION

The optimal functioning of a milking cluster depends on the maintenance of vacuum inside the liner at the teat tip throughout milking. However, in high-line milking systems, milk flow causes a loss of vacuum inside the milk tube, which is particularly large during periods of high milk flow. The vacuum loss occurs mainly because of the vertical transport of milk through the long milk tube and consequently the vacuum inside the teat cup liner decreases (Østerås and Lund, 1980). The vacuum loss in high- and mid-line milking systems depends mainly on the rate of milk transported. The decrease is particularly large during the plateau phase of milk flow (i.e., during constant high milk flow from all 4 quarters), whereas vacuum loss does not occur or only slightly occurs at the start of milking and toward the end of milking when the milk flow rate is relatively low (Østerås and Lund, 1980; Rasmussen and Madsen, 2000; Díaz et al., 2004). Because the magnitude of vacuum decrease changes during the course of milking, it cannot be compensated for by a general increase of the vacuum level in the milk tube. Consequently, if the vacuum were increased overall, it would be effective on the teat during periods of no or low milk flow (Isaksson and Lind, 1992), increasing the risk of teat tissue damage including hyperkeratosis of the teat canal (Neijenhuis et al., 2001).

Milking machine settings affect both milking characteristics and teat tissue condition (Smith and Petersen, 1946; Smith et al., 1974; Thomas et al., 1991). Low vacuum inside the liner may reduce liner closure and result in less pressure acting on the teat during the massage phase. Additionally, if the transport of milk from the teat through the short milk tube is based on a low vacuum, the vacuum can reverse at the moment of liner opening during the a-phase of pulsation, potentially causing a reflux of milk back from the claw to the teat tip and into the udder (Thompson and

Received January 6, 2010.

Accepted April 14, 2010.

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Miller, 1974). This effect may increase the risk of cross-infections between quarters.

In general, machine milking causes transient edema in the teat tissue, which is most apparent immediately after milking and recovers after a few minutes (Hamann and Mein, 1988). The degree of tissue change and recovery time of teat tissue after milking increased with increasing vacuum levels (Hamann et al., 1993). To quantify teat tissue changes, both the cutimeter method (i.e., measurement of the tissue thickness with a spring-loaded caliper; Hamann and Mein, 1988, 1990; Isaksson and Lind, 1992; Hamann et al., 1996) and ultrasound imaging of the teat (Bruckmaier and Blum, 1992; Neijenhuis et al., 2001; Weiss et al., 2004) have been used.

The goal was to evaluate the effects of different milking machine settings causing different degrees of milk flow-dependent vacuum loss during the period of high milk flow on milking characteristics and teat tissue changes. In addition, the suitability and sensitivity of measurements of milking-related teat tissue changes were investigated by using the cutimeter method and longitudinal ultrasound teat cross-sectioning.

MATERIALS AND METHODS

Experimental Animals and Housing

Ten dairy cows (7 Red Holstein, 2 Holstein, and 1 Holstein $\times$ Brown Swiss) from the herd of the Swiss Federal Research Station in Posieux (Agroscope Liebefeld-Posieux) were used in this experiment. They were between 116 and 248 DIM. During the experiment, the cows were in their first (1), second (2), third (3), fourth (2), and fifth (2) lactations.

The mean 305-d milk production was 9,202 kg and ranged from 7,267 to 11,628 kg in the preceding lactation of 7 multiparous cows [1 cow was in her first lactation (4,246 kg/153 d) and 2 multiparous cows did not complete 305 DIM previously (7,251 kg/277 d and 6,575 kg/288 d, respectively)]. The animals were kept in loose housing.

Experiment 1: Milking and Milk Flow Recording

The cows were exclusively milked by one person throughout the experiment. The time from the first touch of the mammary gland to cluster attachment was 1 min (forestripping and cleaning, manual teat stimulation).

For milking, the cows were transferred into a tie stall barn and were milked with a high-line milking system (DeLaval, Tumba, Sweden) at 0500 h (13 h after previ-

ous milking) and at 1600 h (11 h after previous milking). The milk line was mounted 1.91 m above cow standing level. Milking clusters were DeLaval Harmony Plus with liner model 999009-82 (DeLaval). The weight of the complete cluster was 1.7 kg.

The experiment started after 2 d of adaptation (d -1 and 0) to the cluster. Two milking machine units: MilkMaster (MM) and DelPro (DP) (both from DeLaval) were compared in a crossover design; 5 cows started with the MM and 5 cows with the DP (d 1 to 7). On d 8 the machines (treatments) were changed between cow groups (d 8 to 14). Milk yield and milk flow were recorded during all milkings throughout the experiment by using mobile milk flow recorders (LactoCorder, WMB AG, Balgach, Switzerland).

MilkMaster. Until reaching a flow of 0.2 kg/min, the MM milked at a vacuum level of 33 kPa, with a pulsation rate of 50/min and a pulsation ratio of 30:70 (Duovac settings). When the milk flow increased beyond 0.2 kg/min, vacuum and pulsation changed into the main milking period with a delay of <4 s, where the system vacuum level was 49 kPa, the pulsation rate 60/min, and the pulsation ratio 65:35. These settings were maintained until the flow decreased below 0.2 kg/min when vacuum and pulsation switched again to the Duovac settings with a delay of 5 to 9 s to the end of milking. The cluster removal was activated automatically 20 s after milking with the Duovac (vacuum turned off and the cord was pulled in after 3.5 s). The vacuum in the short milk tube without milk flow was 47.2 kPa if the cluster was attached.

DelPro. The DP system comprised a regulating valve in the long milk tube where the vacuum was continuously adjusted to achieve a more constant vacuum level at the teat tip at all different milk flow rates throughout the milking period. The adjustment was based on the actual milk flow (rough regulation) and on the vacuum at the regulating valve itself (fine regulation).

Up to a flow of 0.2 kg/min, the DP milked at a vacuum level of 33 kPa, with a pulsation rate of 50/min and a pulsation ratio of 30:70 (Duovac), similar to the MM. There was an initial fixed delay for high milk flow of 15 s; that is, even if milk flow was above 0.2 kg/min immediately after cluster attachment, the DP milked for 15 s with the Duovac settings. Above a milk flow of 0.2 kg/min, vacuum and pulsation settings changed into the main milking period (after a delay of <4 s), where the system vacuum level was 56 kPa, the pulsation rate 60 cycles/min, and the pulsation ratio 65:35. These settings lasted until the flow decreased again below 0.2 kg/min. Thereafter, the Duovac settings started again with a delay of about 4 s. The cluster removal was activated automatically 20 s after milking with the

Duovac (vacuum turned off and the cord was pulled in after 3.5 s). The vacuum in the short milk tube without milk flow was 43.5 kPa if the cluster was attached.

During all experimental milkings, the milking characteristics calculated by the LactoCorder Software (Version 5.2.0 Beta 49 software, WMB AG) were used for evaluation. The measures used were total milk yield (**TMY**), main milking time (**MMT**; time from milk flow >0.5 kg/min at the start of milking to <0.2 kg/min at the end of milking), peak flow rate (**PFR**; highest milk flow maintained for at least 22 s), time until peak flow rate (**tPFR**), average milk flow during MMT (**AMF**), duration of incline (**dI**; duration from a milk flow of 0.5 kg/min at the start of milking until milk flow reached a plateau; i.e., the slope of the increasing milk flow reached a threshold of <0.8 kg/min²), duration of plateau (**dP**; after incline until milk flow dropped to a negative slope of >0.8 kg/min²), duration of decline (**dD**; after plateau until 0.2 kg/min) and the total milking time (**TMT**; start of milking until manual switch-off of the LactoCorder recording, which was done immediately before cluster removal).

Vacuum Patterns

Vacuum recordings were performed during evening milkings once for the MM and once for the DP. The vacuum acting on the left front teat tip was measured through pressure probes in the short milk tube and was calculated by the LabVIEW software 8.6 (National Instruments, Kista, Sweden). Vacuum data were recorded every 0.1 s throughout milking, and a running mean was calculated every 1.5 s. Based on these data, the maximum and minimum of the main milking period were used to calculate the vacuum loss. In case of an ingress due to liner slip during the course of milking that caused a spontaneous vacuum drop (1 animal only, similarly in both treatments), this part of the vacuum curve was excluded from the evaluation.

Teat Ultrasound Imaging

Longitudinal cross-section ultrasound images (Bruckmaier and Blum, 1992; Weiss et al., 2004) of 1 front and 1 rear teat were obtained from each experimental animal before the start of the experiment (d 1) and on the last day of the treatment periods (d 7 and 14). The ultrasound (EchoWave 3.37 tpm, Lüneburg, Germany) was always recorded immediately after milking (5 cows in the morning, 5 cows in the evening) by b-mode ultrasound (5-MHz probe) with the teat in a cup of hand-warm water. The ultrasound probe was applied to the outside of the cup by using ultrasound gel. Teat diameter, teat wall thicknesses (average of both walls

of the cross section was used for data evaluation), and teat canal length were evaluated 2.5 cm above the teat tip.

SCC

Proportional composite milk samples were taken from the morning milking on d 0, 7, and 14 to measure SCC by the use of the DeLaval cell counter (DCC).

Experiment 2: Validation and Comparison of Methods to Measure Teat Tissue Condition

During an additional morning milking, when milking was performed with the DP, teat tissue thickness (at 2.5 cm from the teat tip) was measured with the cutimeter as described previously (Hamann and Mein, 1988; Hamann et al., 1996) and by using teat ultrasound (Weiss et al., 2004). Each teat (10) was measured twice (immediately after milking and 20 min after milking). This experiment was performed to compare the results obtained by using a cutimeter and by ultrasound on teat tissue changes during milking and following recovery within 20 min.

Mathematical and Statistical Evaluations

All data are presented as arithmetic means and standard error of the means (SEM). For statistical evaluation, the Mixed procedure of SAS (release 8.02; SAS Institute Inc., Cary, NC) was used. Differences of means were localized by Bonferroni's *t*-test and considered significant if $P < 0.05$. The model contained treatment, time of milking, parity [first and second parity compared with the rest (multiparous)], and individual cow as the repeated subject. None of the interactions included in the model (treatment by parity, treatment by milking time, and treatment by stage of lactation) were significant. They were excluded from the model. Pearson correlations between PFR and the vacuum loss and between the results obtained by cutimeter and ultrasound were calculated. Linear regression with regression lines through the origin between PFR and vacuum loss were calculated ($\text{vacuum loss} = f \times \text{PFR}$), where *f* is the regression coefficient.

RESULTS

Experiment 1: Milking Characteristics of MM Versus DP

Total milk yield was similar in both treatments (Table 1), but higher at morning than at evening milkings (15.20 ± 0.23 vs. 12.30 ± 0.17 kg); first- and second-

Table 1. Milking characteristics during all morning and evening milkings with the MilkMaster (MM) and DelPro (DP) milking machines (both from DeLaval, Tumba, Sweden)

Characteristic ¹	Treatment	
	MM	DP
TMY, kg	13.7 ± 0.2	13.8 ± 0.2
AMF, kg/min	2.77 ± 0.06	2.86 ± 0.07
PFR, kg/min	4.29 ± 0.07 ^a	4.74 ± 0.08 ^b
tPFR, min	1.68 ± 0.05	1.62 ± 0.04
MMT, min	5.34 ± 0.15	5.25 ± 0.13
TMT, min	5.91 ± 0.14	5.65 ± 0.12
dI, min	0.64 ± 0.02	0.66 ± 0.02
dP, min	1.96 ± 0.07 ^a	1.57 ± 0.06 ^b
dD, min	2.74 ± 0.13	3.02 ± 0.13

^{a,b}Means within a row with different superscripts differ ($P < 0.05$).

¹TMY = total milk yield; MMT = main milking time; AMF = average milk flow during MMT; PFR = peak flow rate; tPFR = time to reach PFR; TMT = total milking time; dI = duration of incline; dP = duration of plateau; dD = duration of decline.

parity cows produced less milk than did multiparous cows (12.91 ± 0.21 vs. 14.11 ± 0.21 kg; $P < 0.05$). Total milk yield was significantly higher in mid than in late lactation (14.01 ± 0.21 vs. 13.17 ± 0.26 kg). The changeover of the treatments MM and DP did not cause a transient reduction in udder emptying. Thus, daily milk yields on the last day before and on the first day after the treatment change were similar (MM = 14.50 ± 0.19 kg and DP = 14.46 ± 0.19 kg, respectively).

Peak flow rate was higher with the DP than with the MM (Table 1; $P < 0.05$), whereas AMF did not differ between treatments. In this experiment, first- and second-parity cows had significantly lower PFR than did multiparous cows (4.33 ± 0.11 vs. 4.59 ± 0.06 kg/min).

Time until peak flow rate, MMT, TMT, and dI did not differ significantly between treatments (Table 1). Time until peak flow rate was significantly less at evening milkings than at morning milkings (1.55 ± 0.03 vs. 1.75 ± 0.05 min) and was significantly greater in mid lactation than in late lactation (1.72 ± 0.04 vs. 1.50 ± 0.05 min). Main milking time and TMT were shorter in the evening milkings (4.85 ± 0.13 ; 4.88 ± 0.12 min) compared with morning milkings (5.57 ± 0.13 ; 5.74 ± 0.14 min) and in first- and second-parity cows (4.55 ± 0.14 ; 5.16 ± 0.11 min) compared with multiparous cows (5.16 ± 0.11 ; 5.62 ± 0.12 min; $P < 0.05$). Main milking time and TMT were significantly longer in mid lactation than in late lactation (5.24 ± 0.12 and 5.65 ± 0.13 min vs. 4.51 ± 0.09 and 5.21 ± 0.09 min). Duration of incline was significantly longer in multiparous cows than in first- and second-parity cows (0.70 ± 0.02 vs. 0.54 ± 0.02 min).

Duration of plateau was shorter if milking was performed with the DP than with the MM (Table 1; $P < 0.05$). The dP was significantly longer in mid lactating

cows compared with late lactating cows (1.89 ± 0.06 vs. 1.48 ± 0.08 min) and significantly longer in the morning milkings compared with the evening milkings (2.03 ± 0.07 vs. 1.89 ± 0.06 min).

Duration of decline was not significantly different between treatments. It was shorter in first- and second-parity cows than in multiparous animals (2.21 ± 0.10 vs. 3.17 ± 0.12 ; $P < 0.05$) and was significantly longer in mid than in late lactation (3.10 ± 0.12 vs. 2.37 ± 0.12 min).

Vacuum Patterns

The vacuum at the teat tip decreased in both treatments during the period of high milk flow. The vacuum loss during the whole milking was significantly lower with the DP compared with the MM (11 ± 1.1 vs. 15 ± 0.7 kPa; $P < 0.05$). The vacuum loss was always higher during high milk flow for all treatments. Slower milking cows (AMF < 4 kg/min with the MM and DP, respectively) had a vacuum loss of 11.54 to 13.29 kPa with the MM and a loss of 4.50 to 5.95 kPa with the DP. Fast milking cows (AMF > 4 kg/min with the MM and DP, respectively) had a vacuum loss of 13.66 to 18.02 kPa with the MM and a loss of 9.78 to 15.12 kPa with the DP (Figure 1). Pearson correlation between PFR and the vacuum loss was $r = 0.81$ ($P < 0.05$) for the MM and $r = 0.96$ ($P < 0.05$) for the DP. The corresponding regression coefficient (f) was 3.52 for the MM and 2.36 for the DP, demonstrating a smaller vacuum loss with the DP than with the MM.

Teat Ultrasound Imaging

None of the evaluated anatomical teat characteristics (teat diameter, teat wall thickness, and canal length) recorded by ultrasound differed between treatments (Table 2). No macroscopic changes of teats were observed throughout the experimental period.

SCC

The mean SCC of proportional composite milk samples, taken from the morning milkings, were $102 \pm 19 \times 10^3$ on d 0, $76 \pm 10 \times 10^3$ on d 7, and $91 \pm 11 \times 10^3$ cells/mL on d 14. No significant changes of SCC were recorded throughout the experiment. Thus, SCC was in the expected range for healthy cows free of IMI.

Experiment 2

The measured data obtained by cutimeter and ultrasound are in Figure 2. Pearson correlation (r) was 0.71 ($P < 0.05$) for the 20 measurements when the cutimeter

Figure 1. Milk flow curve (thick curve) and vacuum curve in the short milk tube (thin curve) for individual cows with low peak flow rate (PFR) (cow 1519), mid PFR (cow 1535), and high PFR (cow 1541) during milking with the MilkMaster (MM; left panels) and the DelPro (DP; right panels), respectively. Both milking machines are from DeLaval (Tumba, Sweden).

Figure 2. Linear regression (—) of ultrasound (US) and cutimeter of 2 time points: immediately after milking (x) and 20 min after milking (●). The connecting line between 2 points (—) shows the recovery.

was compared with the ultrasound (to measure average teat wall thickness). In addition, changes during the recovery period were calculated from both ultrasound and cutimeter measurements, and Pearson correlation was calculated for the effective recovery (the difference of the value 20 min after milking and that immediately after milking; $r = 0.85$, $P < 0.05$) and for the relative recovery [percentage of the value at 20 min after milking (100%) relative to the value immediately after milking; $r = 0.85$, $P < 0.05$].

DISCUSSION

The TMY, which did not change throughout the experiment, indicated complete emptying of the mammary gland in both treatments. The different magnitude of vacuum decrease was obviously not a relevant factor to influence the completeness of udder emptying.

The PFR was higher with the DP than with the MM, whereas AMF did not differ between treatments. This finding is not surprising because milk ejection is a con-

tinuous process (Bruckmaier et al., 1994) and the milk transferred from the alveolar tissue into the cisternal cavities (milk ejection rate) can be limiting for milk flow rate in particular if cisternal filling is low (Pfeilsticker et al., 1995). Just before milking and after prestimulation, the cistern is well filled with milk; therefore, milk flow rate during the early phase of milking is mainly affected by teat anatomy and the type of liner, vacuum, and pulsation (Hamann and Mein, 1996; Weiss et al., 2004; Spencer et al., 2007). With a higher or more constant vacuum at the teat tip, such as provided by the DP, milk that is available in the cistern can be removed faster and the PFR increases (Baxter et al., 1950; Stewart and Schultz, 1958; Rasmussen et al., 1986). Because the udder cistern was usually well filled after the start of milk ejection during early milking (Bruckmaier et al., 1994), it was not surprising that the dP was shorter with the DP than with the MM treatment. The end of the dP was reached when the delivery of milk from the alveoli into the cistern was slowing because of the gradual emptying of the alveoli; that is, the milk ejection rate was decreasing (Bruckmaier et al., 1994). No adjustment of the milking machine can influence the course of milk ejection, because the physiological process of milk transfer into the cistern is not under the influence of vacuum or pulsation. Thus, the milk ejection rate can be a limiting factor for milk flow toward the end of milking and a flat decline of milk flow in each quarter likely represented the decline of milk ejection rate (Pfeilsticker et al., 1995). Despite higher PFR and reduced dP with the DP compared with MM, the AMF was not increased. Fast milk removal during early milking caused a particularly slow milk removal during the late stages of milking because there was likely less milk in the cistern at the end of dP to compensate for the decreasing milk ejection rate. Because TMY and AMF did not change between the treatments, MMT did not differ between treatments.

The vacuum at the teat tip in a high-line milking system decreases during high milk flow (Østerås and Lund, 1980; Rasmussen and Madsen, 2000); this also occurs

Table 2. Ultrasound measurements immediately after morning milking with MilkMaster (MM) and DelPro (DP) milking machines (both from DeLaval, Tumba, Sweden)

Item	Time point of measurement		
	Before trial	After MM	After DP
Front teat			
Canal length, mm	11.7 ± 0.6	11.7 ± 0.4	11.9 ± 0.4
Teat diameter, mm	26.8 ± 0.6	26.3 ± 0.5	26.5 ± 0.4
Wall thickness, mm	9.6 ± 0.3	9.4 ± 0.4	9.9 ± 0.4
Rear teat			
Canal length, mm	12.2 ± 0.5	12.6 ± 0.5	12.2 ± 0.3
Teat diameter, mm	26.8 ± 0.6	27.4 ± 0.7	27.1 ± 0.8
Wall thickness, mm	9.1 ± 0.4	8.7 ± 0.4	8.9 ± 0.4

to some extent in mid-line milking systems (Díaz et al., 2004; Gleeson et al., 2003). The DP milking machine stabilized the vacuum via milk flow-dependent adjustments, which was expressed by a lower vacuum drop at high milk flow rates with the DP compared with the MM machine. Thus, the regression coefficient for the milk flow-dependent vacuum loss was smaller in the DP than in the MM. One additional milking was performed to test the effect of the LactoCorder on the vacuum during high milk flow. Milking with the LactoCorder caused an additional vacuum drop in MM and DP of up to 2.5 kPa (similar in both treatments) during high milk flow (around 5.5 kg/min; data not shown).

Teat tissue condition and udder health status were studied by recording the SCC and the teat tissue changes measured with ultrasound, respectively. Similar to the results of Gleeson et al. (2003, 2004), but in contrast to those of Hamann and Mein (1988) and Hamann et al. (1993), even if the DP was milking at a higher vacuum level during the entire milking period, there was no increase in teat wall thickness that would indicate the presence of higher edema. The values were similar in both treatments. The SCC was constant over the entire experimental period, supporting the results of Rasmussen and Madsen (2000). Thus, during the duration of the experiment, teat tissue condition and udder health status did not change, whether cows were milked with the DP or with the MM.

In experiment 2, the high correlation showed that both ultrasound and cutimeter are useful for measuring teat tissue condition and changes, in contrast to the results of Neijenhuis et al. (2001). Teat ultrasound provides a real image of the entire teat and can be used for the evaluation of a variety of measures, whereas the cutimeter shows the degree of fluid accumulation in the teat (Hamann and Mein, 1988).

In conclusion, milking with the DP resulted in higher PFR and shorter dP compared with milking using the MM. Mean milking time, TMY, and AMF remained unchanged. The DP stabilized the vacuum at the teat and resulted in less vacuum loss compared with the MM. Udder health (based on SCC) and postmilking teat condition remained unchanged independent of vacuum changes during milking, at least during the relatively short duration of the current trial.

The cutimeter and teat ultrasound were both useful measures of teat tissue changes. However, teat ultrasound provided more information on various measures of the teat compared with the cutimeter method.

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