J. Dairy Sci. 101:649–660
https://doi.org/10.3168/jds.2017-12942

A method for assessing teatcup liner performance during the peak milk flow period

J. F. Penry,*[1] J. Upton,† S. Leonardi,‡ P. D. Thompson,§ and D. J. Reinemann§
*Department of Dairy Science, University of Wisconsin-Madison, Madison 53706
†Animal and Grassland Research and Innovation Centre, Teagasc Moorepark, Fermoy, Co. Cork, Ireland P61P302
‡Department of Health, Animal Science and Food Safety, Universita degli Studi di Milano, 20133 Milano, Italy
§Department of Biological Systems Engineering, University of Wisconsin-Madison, Madison 53706

ABSTRACT

The objective of this study was to develop a method to quantify the milking conditions under which circulatory impairment of teat tissues occurs during the peak flow period of milking. A secondary objective was to quantify the effect of the same milking conditions on milk flow rate during the peak flow rate period of milking. Additionally, the observed milk flow rate was a necessary input to the calculation of canal area, our quantitative measure of circulatory impairment. A central composite experimental design was used with 5 levels of each of 2 explanatory variables (system vacuum and pulsator ratio), creating 9 treatments including the center point. Ten liners, representing a wide range of liner compression (as indicated by overpressure), were assessed, with treatments applied using a novel quarter-milking device. Eight cows (32 cow-quarters) were used across 10 separate evening milkings, with quarter being the experimental unit. The 9 treatments, with the exception of a repeated center point, were randomly applied to all quarters within each individual milking. Analysis was confined to the peak milk flow period. Milk flow rate (MFR) and teat canal cross sectional area (CA) were normalized by dividing individual MFR, or CA, values by their within-quarter average value across all treatments. A multiple explanatory variable regression model was developed for normalized MFR and normalized CA. The methods presented in this paper provided sufficient precision to estimate the effects of vacuum (both at teat-end and in the liner mouthpiece), pulsation, and liner compression on CA, as an indicator of teat-end congestion, during the peak flow period of milking. Liner compression (as indicated by overpressure), teat-end vacuum, vacuum in the liner mouthpiece, milk-phase time, and their interactions are all important predictors of MFR and teat-end congestion during the peak milk flow period of milking. Increasing teat-end vacuum and milk-phase time increases MFR and reduces CA (indicative of increased teat-end congestion). Increasing vacuum in the liner mouthpiece also acts to reduce CA and MFR. Increasing liner compression reduces the effects of teat-end congestion, resulting in increased MFR and increased CA at high levels of teat-end vacuum and milk-phase time. These results provide a better understanding of the balance between milking speed and milking gentleness.

Key words: liner performance, peak milk flow, vacuum, pulsation, congestion

INTRODUCTION

One practical limitation to increasing milking speed by increasing milking vacuum or pulsation ratio is the resulting stresses on teat tissues, associated discomfort for cows, and potential increase in mastitis risk. Whereas the vacuum and pulsation conditions that affect milking speed have been widely studied, liner properties and milking conditions under which teat tissue congestion occurs have not been well quantified.

Increasing milking vacuum was shown by Williams et al. (1981) to increase milk flow rate (**MFR**) while also increasing teat-end congestion and decreasing teat canal cross section area. In a trial assessing 3 levels of milking system operating vacuum (**Vs**), increasing vacuum from 30 to 50 kPa resulted in an increase in teat-end thickness as measured with a cutimeter (Hamann and Mein, 1988). Mein and Reinemann (2007) reported that increasing Vs from 40 to 50 kPa produced a 20% change in MFR, with the dominant effects occur during the peak flow period of milking. Williams and Mein (1986) and Ambord and Bruckmaier (2010) found a significant increase in peak milk flow rate (**PMF**) when Vs was automatically increased with increasing MFR. O'Callaghan and Gleeson (2004) concluded that teat-end vacuum during the b-phase of pulsation is positively correlated with MFR and negatively correlated with total milking time.

Hamann and Mein (1996) reported that pulsation settings that increased MFR (shorter d-phase and longer

---

Received March 27, 2017.
Accepted September 1, 2017.
[1] Corresponding author: penry@wisc.edu

b-phase) also increased postmilking teat-end thickness. Those authors also noted that the effect of liner was at least as large as the effects of pulsation, but only tested 2 liners. Gleeson et al. (2004) found that increasing pulsator ratio from 0.60 to 0.67 shortened total milking time, although MFR was not specifically measured. Mein et al. (2004) reported that MFR reached a maximum for pulsator ratios between 0.60 and 0.70 and that a reduction in MFR seen at pulsator ratio of 0.80 is probably due to insufficient time for congestion to be relieved during the d-phase of pulsation.

Liner compression, as defined by Mein et al. (2003), can also have an influence on MFR. Overpressure (**OP**) is a biologically relevant indicator of liner compression (Leonardi et al., 2015). Williams and Mein (1986) controlled liner compression through changes in pulsation chamber pressure and noted a decrease in MFR with decreased liner compression. Bade et al. (2009) found that increasing vacuum, b-phase duration, and liner compression increased PMF at the udder level, with the effects of liner compression most pronounced at high milking vacuum levels.

Teat-end congestion (or the accumulation of fluids in teat-end tissues) can influence MFR by reducing teat-canal cross sectional area (Upton et al., 2016b). This is based on the assumption that the outer skin layers of the teat-end are nearly fully distended at vacuum levels above about 40 kPa (Williams et al., 1981) and the resulting swelling of the soft inner tissues of the teat-end cause the canal to become restricted. Understanding how milking machine settings influence teat congestion is also important with regard to IMI risk. Hamann et al. (1993) postulated that the efficiency of local and systemic defense mechanisms might be impaired due to congestion after milking at higher Vs. Congestion effects might impair immunological function in 2 ways: first, through an increased time for teat canal closure after cluster removal and, second, via direct effects on immunological defense mechanisms (Paulrud, 2005). An association between higher MFR and the risk of new IMI has also been reported (Grindal and Hillerton, 1991). The objective of our study was to develop a method to quantify the conditions under which circulatory impairment of teat tissues occurs during the peak flow period of milking. A secondary objective was to quantify the effect of the same milking conditions on MFR during the peak flow rate period of milking, with both objectives providing guidance to users on the physiological limitations to increasing milking speed.

MATERIALS AND METHODS

The experiment was carried out at the University of Wisconsin-Madison Dairy Cattle Center and was approved under institutional animal care and use committee animal use protocol A005167. Milking was done using the quarter-milking device described by Upton et al. (2016a) and illustrated in Figure 1. Vacuum levels in the pulsation chamber, short milk tubes (**Vsmt**), mouthpiece chambers (**Vmpc**), and cumulative milk weight for each quarter were recorded at a sampling rate of 1,000 Hz.

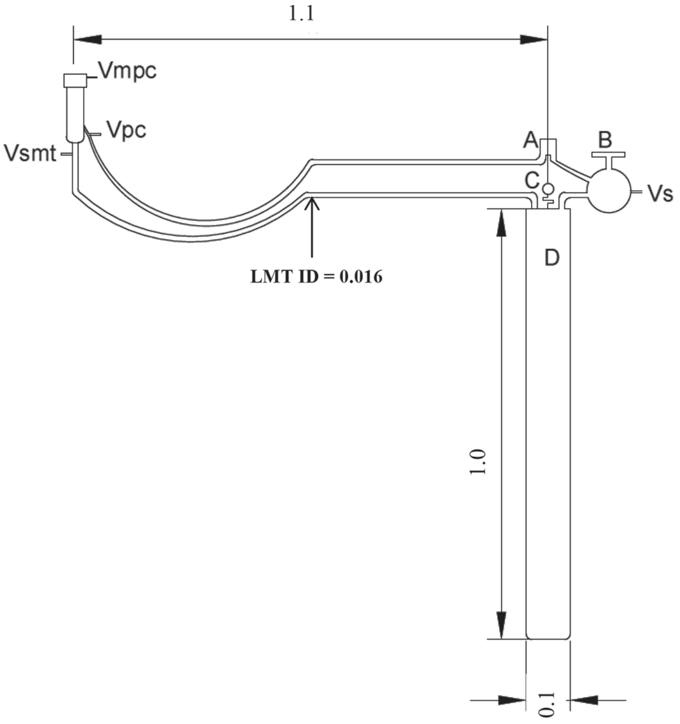

Figure 1. Diagram of 1 teat-cup arrangement of the quarter milking analysis device. A = pulsator; B = vacuum regulator; C = weigh cell; D = milk collection tube; Vs = milking system operating vacuum; Vmpc = mouthpiece chamber vacuum measurement point; Vpc = pulsation chamber vacuum; Vsmt = short milk tube vacuum; LMT = long milk tube. Dimensions in meters.

We used an inscribed central composite experimental design (Box and Wilson, 1951), with 5 levels of both pulsator ratio (from 0.50 to 0.70) and Vs (from 37 to 50 kPa) as the explanatory variables (Figure 2) and MFR and cross sectional area of the teat canal (**CA**) as the response variables. The pulsation rate was adjusted to maintain a rest (c+d) phase of 400 ms so that the main effect of changing pulsation ratio was to change the milk (a+b) phase, which ranged from 400 to 933 ms. One of 10 different liners was used for all of the 8 experimental cows at each afternoon milking session. The physical characteristics of the liners are summarized in Table 1. Overpressure was measured for each liner according to the method described in Leonardi et al. (2015).

All cows were prepared for milking with a teat disinfectant and wiped with a clean cloth before attachment

Table 1. Experimental liner characteristics

Liner	Material[1]	Shape[2]	MPC[3] depth (mm)	MPC diameter (mm)	Mid-barrel diameter (mm)	Wall thickness (mm)	Venting[4]	OP[5] (kPa)
A	NR	R	29	21.8	20.8	2.1	None	11.2
B	Si	R	38	22.2	22.8	3.1	None	11.2
C	Si	R	36	22.0	21.6	2.3	None	8.5
D	Si	S	31	21.1	19.9	2.7	SMT	8.5
E	NR	R	29	21.0	21.9	2.3	None	15.5
F	NR	R	31	21.0	22.1	2.2	None	18.1
G	NR	T	35	21.0	21.0	2.0	MPC	9.8
H	NR	T	29	21.0	21.0	1.8	None	10.5
I	NR	T	38	23.6	24.5	2.0	MPC	10.8
J	Si	T	38	21.0	24.0	2.0	SMT	0.0

[1] NR = nitrile rubber; Si = silicon.

[2] R = round; S = square; T = triangular.

[3] MPC = mouthpiece; MP depth measured with 40 kPa applied to short milk tube.

[4] SMT = venting in short milk tube; MPC = venting in mouthpiece chamber.

[5] OP = overpressure (limited pulsation).

after about 1 min according to the standard operating procedure of the parlor. The treatment sequence started with the center-point (T9) followed by 2 randomly applied treatments (T1–T8) and continued in this way with the center-point repeated every 3 treatments until visual assessment indicated that milking was complete in all 4 quarters of the cow. Each treatment was applied for a minimum of 8 s, which corresponded to 7 to 10 complete pulsation cycles, depending on the treatment. Data from the first 3 complete pulsation cycles of each

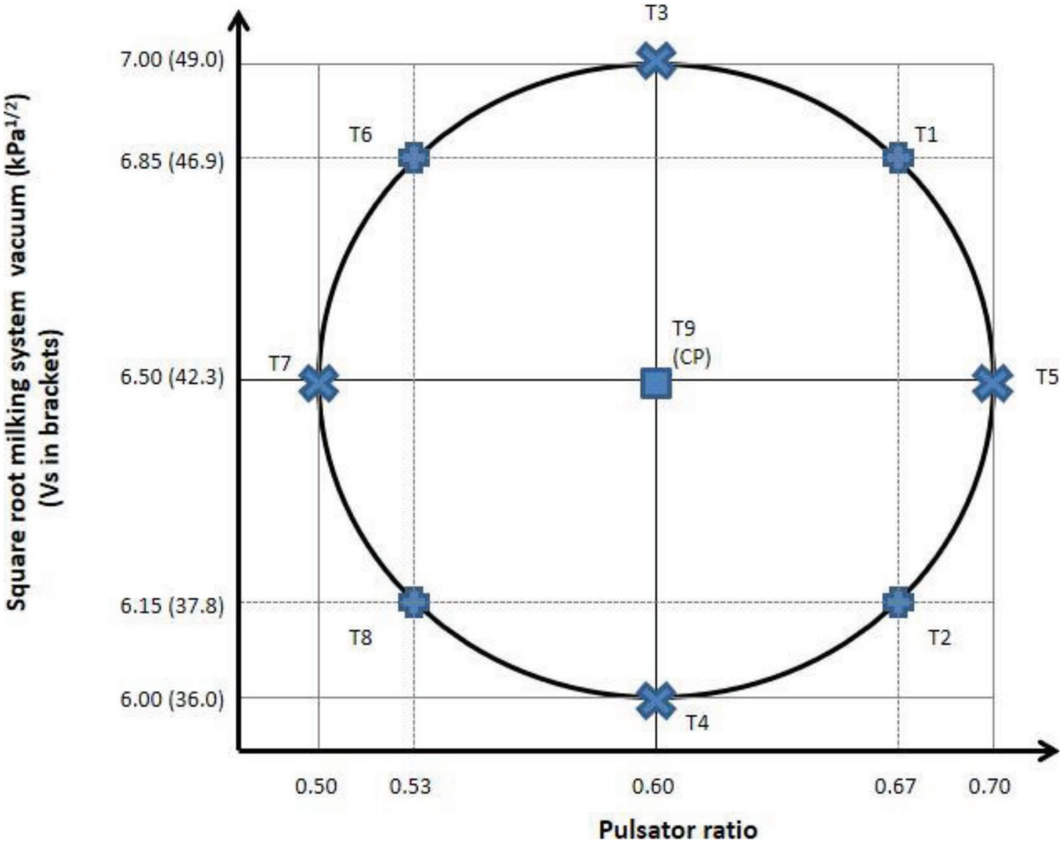

Figure 2. Nine treatments (T) and center point treatment (CP) for 2 explanatory variable inscribed central composite experimental design. Explanatory variable on the vertical axis is milking system operating vacuum (Vs). Explanatory variable on the horizontal axis is pulsator ratio. Explanatory variable settings for each T were designed to be equidistant from the CP. Color version available online.

treatment were removed from the analysis to minimize potential carryover effects between treatments. Milk flow rate was calculated as the slope of a regression between milk weight and time over the remaining complete pulsation cycles for each treatment. Treatment averages were calculated for Vsmt and Vmpc over this same time period. The time that milk was flowing during each pulsation cycle (**MT**) was calculated as the time that the pulsation chamber vacuum exceeded the OP value for each liner. The milk fraction or fraction of the pulsation cycle during which milk was flowing was calculated as MT divided by the total duration of the pulsation cycle.

Data processing and statistical analysis was performed in SAS 9.4 (SAS Institute Inc., Cary, NC). Treatment data were included for analysis for the period in which the MFR was maintained within 80% of the maximum center-point MFR for a quarter to ensure that the data analyzed were recorded during the peak flow period for each quarter. Treatment averages of milk fraction, MFR, and Vsmt were used to calculate CA as

$$\mathrm{CA} = \alpha \times \mathrm{MF} \times \mathrm{MFR} \times (\mathrm{Vsmt} + 4.5)^{-1/2}, \qquad [1]$$

where $\alpha = 14.4$, a constant (See Appendix A for derivation); CA = teat canal cross sectional area (mm^2); MF = milk fraction or fraction of time that milk is flowing during an individual pulsation cycle; MFR = milk flow rate (kg/s); and Vsmt = short milk tube vacuum (kPa). This estimate of CA resulted in an average value for all quarters and all conditions of 3.99 mm^2, corresponding to an effective canal diameter of 2.3 mm, in close agreement with the 2 mm diameter estimated by Williams and Mein (1986). Note that the absolute value of CA is not critical to the final analysis, as CA was normalized and all results are based on a change from the within-quarter average of CA as described below.

Quarter was declared the experimental unit in this experiment. The treatment values of MFR and CA were normalized by dividing these by the quarter average for all treatments (**MFRn** and **CAn**, respectively). The SAS REG procedure was used to produce a quadratic model with first order interactions for MFRn with explanatory variables OP, Vmpc, Vsmt$^{1/2}$, and MT. The square root of short milk tube vacuum was chosen instead of Vsmt because of its expected linear relationship to MFR (Reinemann and Mein, 2010). Model terms were removed in a stepwise, backward elimination for terms with $P > 0.05$, producing the final model

$$\begin{aligned}\mathrm{MFRn} &= \beta\mathrm{o} + \mathrm{OP} + \mathrm{Vmpc} + \mathrm{Vsmt}^{1/2} + \mathrm{MT} \\ &+ \mathrm{OP}^2 + \mathrm{Vmpc}^2 + \mathrm{MT}^2 + \mathrm{OP} \times \mathrm{Vsmt}^{1/2} + \mathrm{OP} \\ &\times \mathrm{MT} + \mathrm{Vsmt}^{1/2} \times \mathrm{MT}, \qquad [2]\end{aligned}$$

where βo is the intercept. A similar approach was used to model CAn with explanatory variables OP, Vmpc, Vsmt, and MT, producing the final model

$$\begin{aligned}\mathrm{CAn} &= \beta\mathrm{o} + \mathrm{OP} + \mathrm{Vmpc} + \mathrm{Vsmt} + \mathrm{MT} + \mathrm{OP}^2 \\ &+ \mathrm{Vmpc}^2 + \mathrm{MT}^2 + \mathrm{OP} \times \mathrm{Vsmt} + \mathrm{MT} \times \mathrm{Vsmt}. \qquad [3]\end{aligned}$$

The reduction in CA from its maximum within-quarter treatment average was used as an indicator of teat-end congestion.

Table 2. Results for Equation 2, generalized linear model for quarter-normalized milk flow rate, where OP = liner overpressure (kPa); Vmpc = average mouthpiece chamber vacuum (kPa); Vsmt$^{1/2}$ = square root of short milk tube vacuum (kPa$^{1/2}$); and MT = milk phase time (ms)

Effect	Coefficient	*F* value	*P*-value
OP	-7.19×10^{-2}	−5.80	<0.0001
Vmpc	5.01×10^{-3}	4.20	<0.0001
Vsmt$^{1/2}$	-1.23×10^{-1}	−3.78	0.0002
MT	-7.16×10^{-1}	−2.58	0.0099
OP^2	3.39×10^{-4}	3.80	0.0001
Vmpc^2	1.18×10^{-4}	−4.37	<0.0001
MT^2	-2.10×10^{-1}	−3.85	0.0001
OP × Vsmt$^{1/2}$	9.74×10^{-3}	5.18	<0.0001
OP × MT	1.43×10^{-2}	4.95	<0.0001
Vsqsmt × MT	1.93×10^{-1}	4.66	<0.0001

RESULTS AND DISCUSSION

The results of the final MFRn and CAn models are given in Tables 2 and 3, respectively. The coefficient of variation was 14% for MFRn predictions and 15% for CAn predictions, with standard error of the predictions ranging from 2 to 5%. Response surfaces for MFRn and change in CAn (as an indicator of teat-end congestion) for examples of a high- (F), medium- (G), and low-OP liners (J) are shown in Figures 3, 4, 5, 6, 7, and 8.

A minimum predicted MFRn of about 0.82 (or 82% of the overall individual quarter average) occurred for the lowest values of Vsmt and MT for the medium- and

Table 3. Results for Equation 3, generalized linear model for quarter-normalized canal area, where, OP = liner overpressure (kPa); Vmpc = average mouthpiece chamber vacuum (kPa); Vsmt = short milk tube vacuum (kPa); and MT = milk-phase time (ms)

Effect	Coefficient	*F* value	*P*-value
MT	-4.63×10^{-1}	−3.19	0.0014
Vsmt	-1.90×10^{-2}	−7.74	<0.0001
OP	-3.94×10^{-2}	−6.71	<0.0001
Vmpc	4.00×10^{-3}	3.99	<0.0001
MT^2	-1.17×10^{-1}	−2.48	0.0133
OP^2	7.13×10^{-4}	9.59	<0.0001
Vmpc^2	-1.73×10^{-4}	−4.76	<0.0001
MT × Vsmt	1.29×10^{-2}	4.07	<0.0001
Vsmt × OP	8.66×10^{-4}	6.34	<0.0001

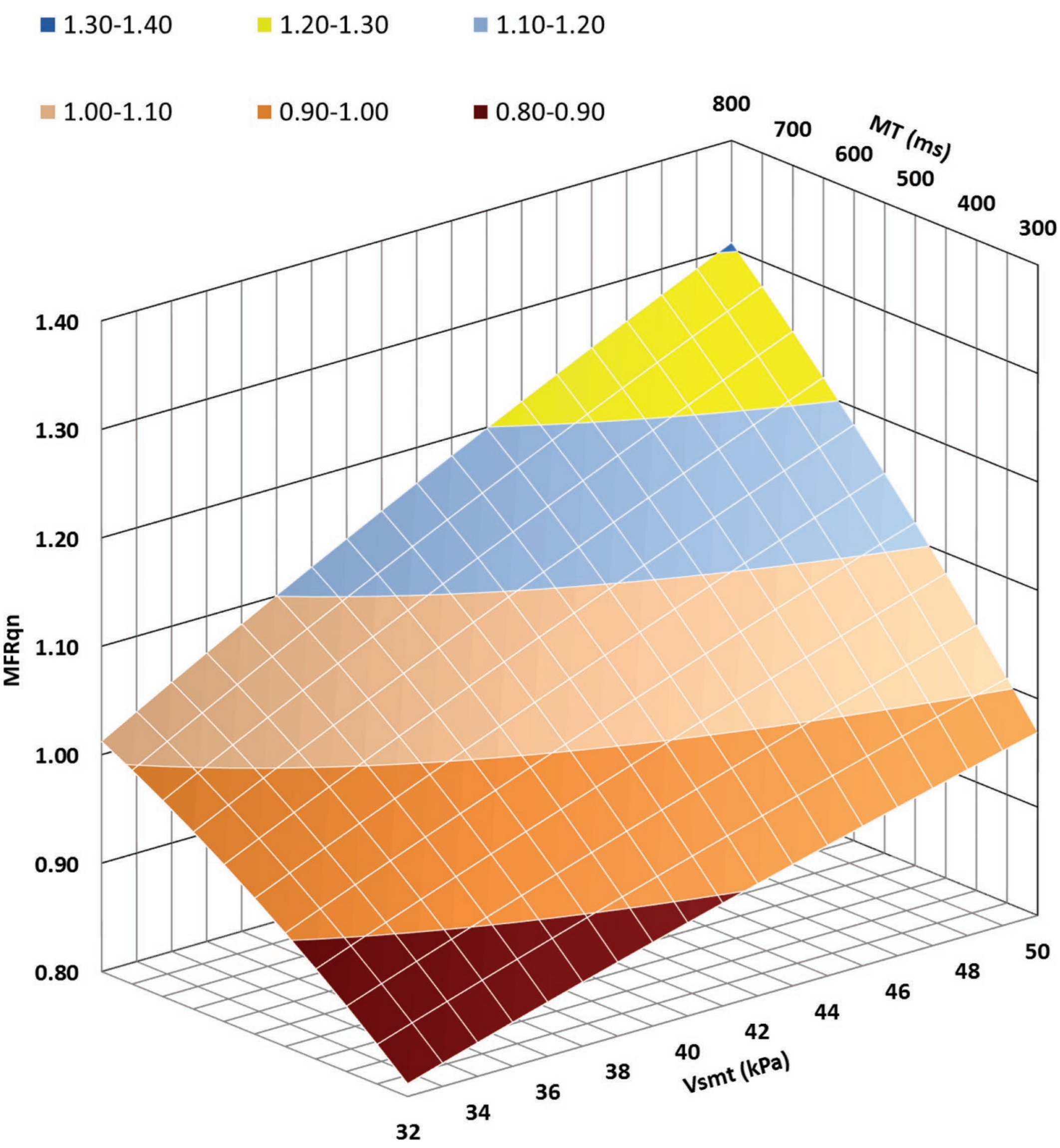

Figure 3. Quarter-normalized milk flow rate (MFRn, dimensionless fraction of quarter-average milk flow rate for all treatments) response to short milk tube vacuum (Vsmt) and milk-phase time (MT) for a high-compression liner (liner F, overpressure = 18 kPa) with rest-phase time held constant at 400 ms. Color version available online.

high-compression liners and was minimally affected by liner OP. The maximum predicted MFRn of about 1.3 (or 30% above the individual quarter average) occurred for the combination of maximum levels of Vsmt, MT and OP. The effect of liner OP was most predominant at high levels of Vsmt and MT, with the low-compression liner reaching a MFRn of 1.05 at these settings. Normalized milk flow rate generally increased with increasing Vsmt, and the range of MFRn increased as liner OP increased. This is most clearly illustrated by comparing MFRn responses in Figures 3, 5, and 7 for a constant value of MT. The interaction between liner OP and both Vsmt and MT is apparent, as the effect of Vsmt on MFRn is more pronounced as both MT and OP increase. When Vsmt was increased from 32 to 50 kPa, the increase in MFRn was about 20% for MT of 300 ms and 30% for MT of 800 ms for the high-compression liner. The medium-compression liner produced MFRn increases of about 5% for MT of 300 ms and 20% for MT of 800 ms. The low-compression liner showed a slight decrease in MFRn for MT of 300 ms and an increase of about 5% for MT of 800 ms.

The minimum predicted teat-end congestion (% reduction in CAn) also occurred for the lowest levels of Vsmt and MT and were minimally affected by OP under these conditions. The maximum predicted teat-

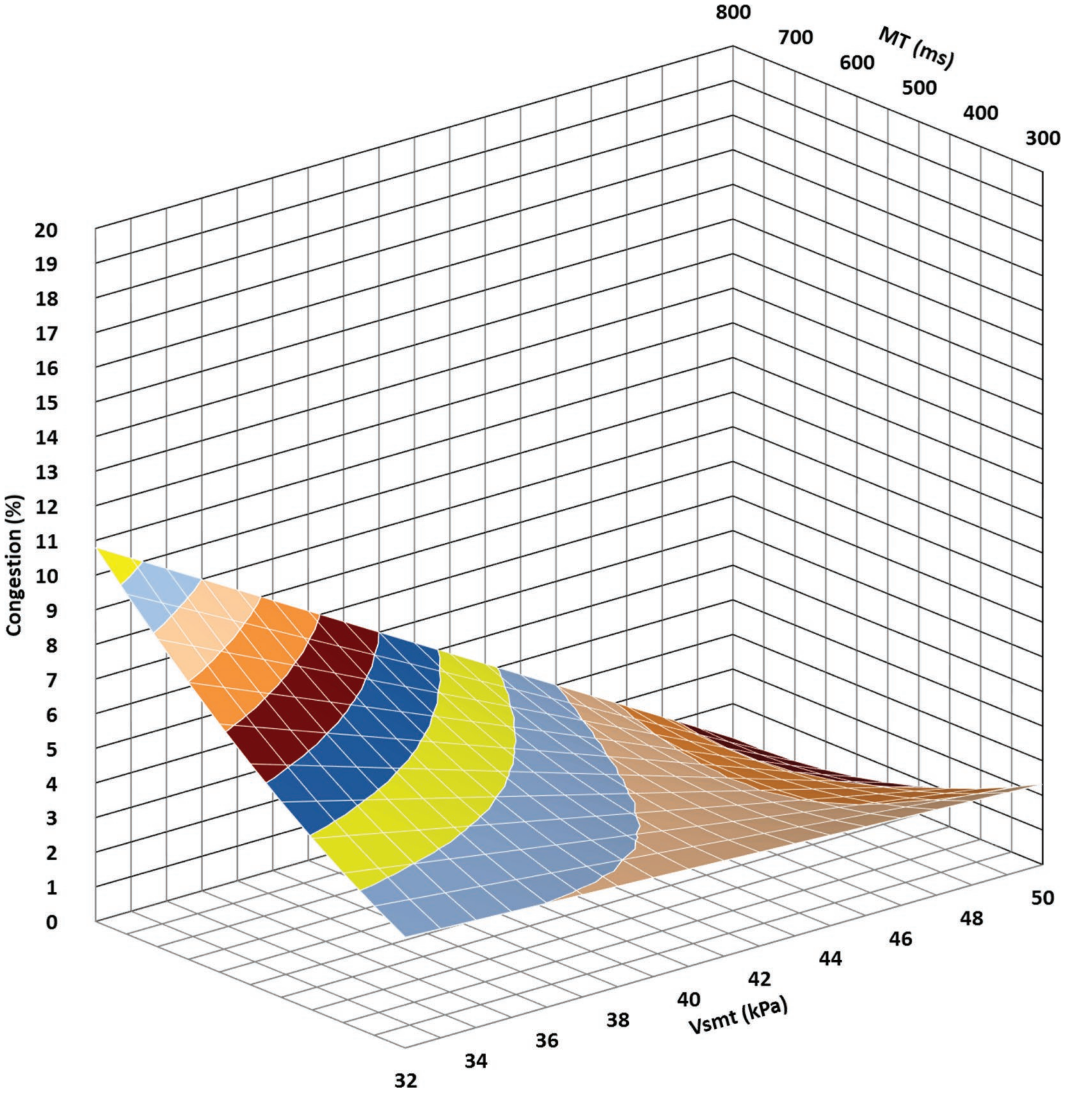

Figure 4. Teat-end congestion (change from maximum quarter-normalized teat canal cross sectional area) response to short milk tube vacuum (Vsmt) and milk-phase time (MT) for a high-compression liner (liner F, overpressure = 18 kPa) with rest-phase time held constant at 400 ms. Color version available online.

end congestion of more than 20% occurred for the low-compression liner at high levels of Vsmt. As an illustration of the interactive effects between liner OP and both Vsmt and MT, the medium-compression liner maintained congestion levels less than 10% and the high-compression liner limited teat-end congestion to less than 1% at these extreme settings.

The trends in MFR predicted in the current work are in general agreement with those reported in previous studies. Ambord and Bruckmaier (2010) noted an increase in PMF where teat-end vacuum was increased, as did O'Callaghan and Gleeson (2004). Peak milk flow rate increased as Vs increased (Hamann and Mein, 1996; Bade et al., 2009); milk flow rate significantly increased at the quarter level when Vs was raised from 40 to 50 kPa (Williams and Mein, 1986). The predicted value of MFRn also increased as MT increased (with corresponding increase in pulsator ratio), which agrees with the trends reported by Bade et al. (2009), Hamann and Mein (1996), and Mein at al. (2004). Gleeson et al. (2004) saw a reduction in total milking time when pulsator ratio was increased from 0.60 to 0.67, but did not report changes in PMF.

Few authors have examined how liner compression affects MFR. Several authors have stated that liner selection is one of the main influences over MFR without directly referring to liner compression (Gleeson et al., 2004; Mein and Reinemann, 2009; Ambord and Bruckmaier, 2010). Liner compression is not specified in the ISO standards (Reinemann et al., 2013), and

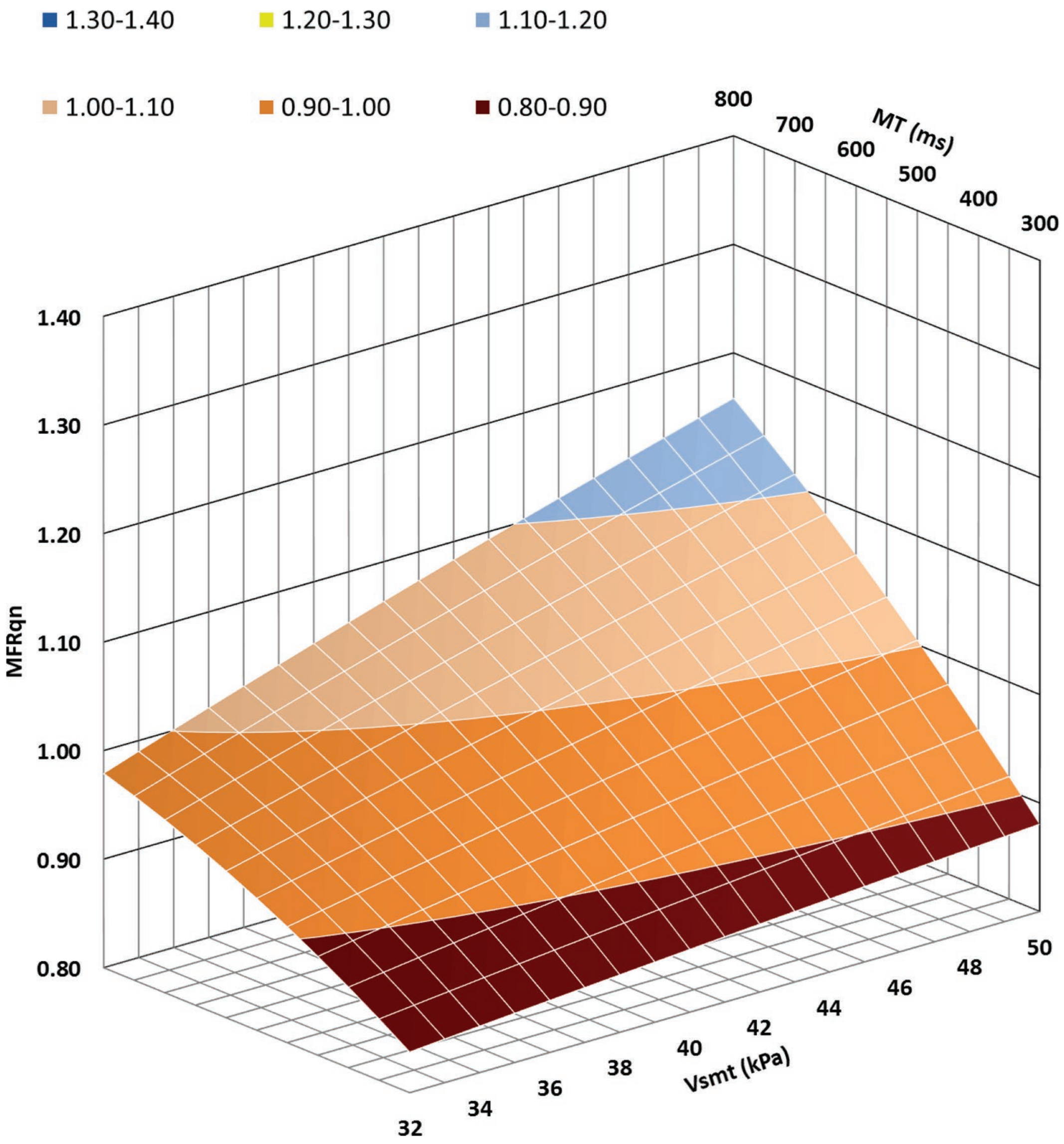

Figure 5. Quarter-normalized milk flow rate (MFRn, dimensionless fraction of quarter-average milk flow rate for all treatments) response to short milk tube vacuum (Vsmt) and milk-phase time (MT) for a medium-compression liner (liner G, overpressure = 9.8 kPa) with rest-phase time held constant at 400 ms. Color version available online.

no formalized industry guidance is offered on this liner characteristic. However, Mein and Reinemann (2007) suggested that a liner OP should not exceed 13 to 14 kPa, which could result in unnecessary and unproductive compression applied to the teat-end. Bade et al. (2009) independently controlled Vs, length of the b-phase, and liner compression (through manipulation of residual vacuum for massage); udder level PMF increased as liner compression was increased and this effect was greatest at higher vacuum, with the authors proposing that teat congestion effects on PMF were more important at higher Vs. Williams et al. (1981) also reported a decrease in quarter-level PMF when liner compression was reduced. Our results show that the effect of liner compression on MFR is considerable and is interactive with both milking vacuum level and pulsation settings.

Teat-end congestion has been reported to reduce CA (Williams et al., 1981), and previous studies have focused on teat-end congestion measured by cutimeter or ultrasonic methods. Increasing Vs was shown to increase teat-end thickness for 2 different liners when milking to a predetermined low MFR (0.2 kg/min) and with a fixed time milking where units were removed during the peak flow period (Hamann and Mein, 1988). Increasing teat-end vacuum was also thought to create

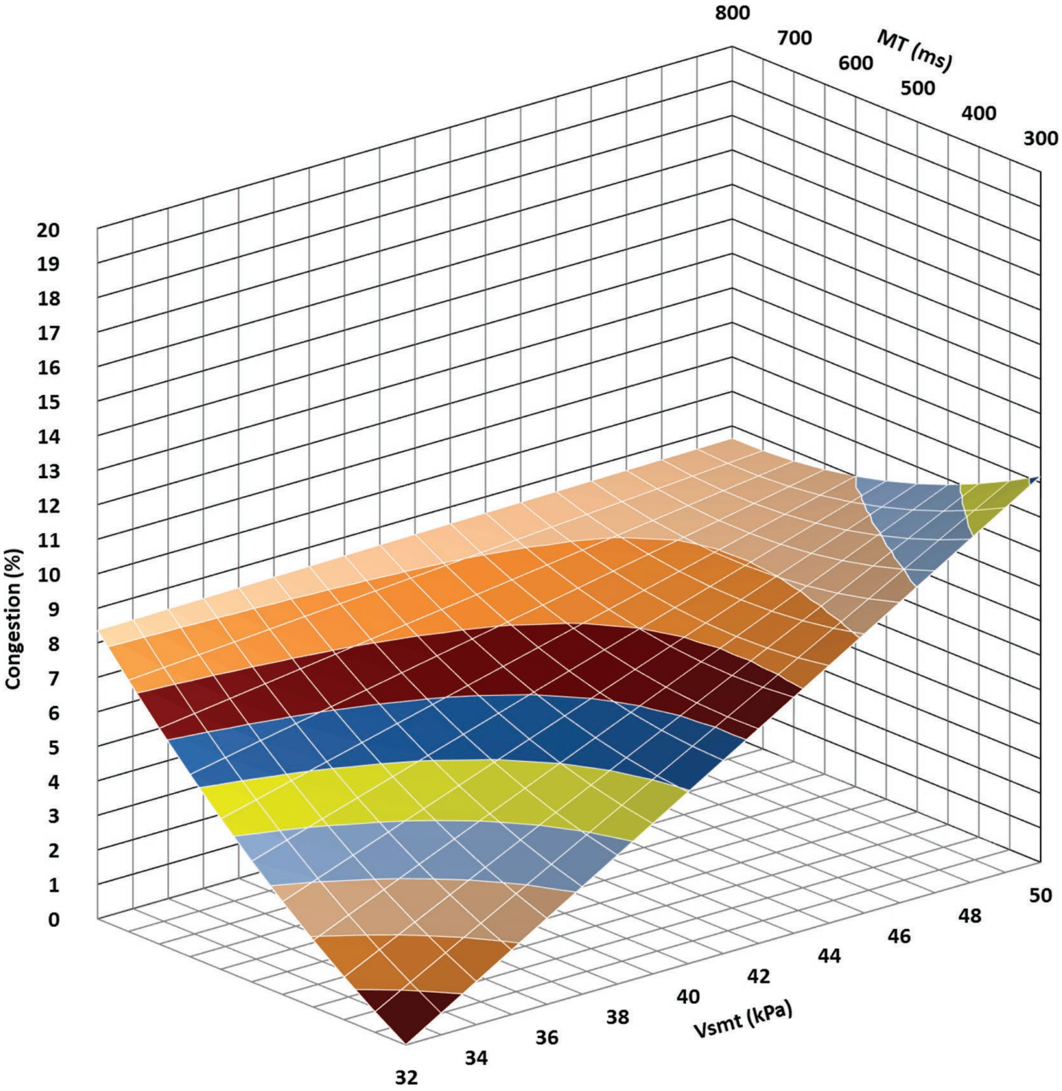

Figure 6. Teat-end congestion (change from maximum quarter-normalized teat canal cross sectional area) response to short milk tube vacuum (Vsmt) and milk-phase time (MT) for a medium-compression liner (liner G, overpressure = 9.8 kPa) with rest-phase time held constant at 400 ms. Color version available online.

higher risk for teat end vascular congestion and edema for 2 different liners (Hamann and Mein, 1996). Mein and Reinemann (2009) reported a critical level of liner OP required to manage teat-end congestion, which increases as the milking vacuum level is elevated. Within pulsation cycle, MFR was observed to decrease once the b-phase duration exceeded 0.5 s, and this reduction was shown to be consistent with vascular congestion at the teat end (Williams et al., 1981). Increased Vs has not been uniformly associated with increased teat-end congestion. Ambord and Bruckmaier (2009) found no significant differences in teat-end thickness via ultrasound examination when Vs was increased from 49 to 56 kPa, resulting in increased MFR. Gleeson et al. (2004) did not report changes in teat tissue parameters where Vs was elevated from 40 to 50 kPa.

The approach taken to estimate teat-end congestion in our experiment did not involve assessment of the tissue directly as in previously reported studies (ultrasound, cutimeter), but rather through an estimate of the cross-sectional area of the teat canal calculated from direct measurement of MFR, MT, and Vsmt, as previously discussed by Bade et al. (2009) and Reinemann and Mein (2010). Williams and Mein (1986) used a method of measuring mass flow rate to estimate CA, finding a reduction in CA of approximately 4% (from 3.14 to 3.02 mm^2), with an associated increase in MFR of 15% as a result of increasing Vs from 40 to 50 kPa.

We found a larger change in CA of approximately 11 to 20% over a similar vacuum change range; however, we also applied a wide range of MT and liner OP. Milk flow rate, Vsmt, and MT measurements must have a high degree of precision to detect these small changes in CA. In a previous experiment, the quarter milking analysis device used in our experiment was shown to be able to detect a change in CA as small as 2% (Upton et al., 2016b). Previous experiments characterizing liner performance have been performed at the udder level (Hamann and Mein, 1996; Gleeson et al., 2004; O'Callaghan and Gleeson, 2004; Ambord and Bruckmaier 2009; Bade et al., 2009; Ambord and Bruckmaier, 2010) or quarter level (Williams et al., 1981; Mein et al., 1987; Williams and Mein, 1986; Butler et al., 1992; Bruckmaier et al., 2004). The distinction is important, as variance in MFR is an order of magnitude smaller at the quarter level compared with at the udder level (Upton et al., 2016a).

Bruckmaier et al. (2004) found that the teat canal starts to unfold at a vacuum level that is quite repeatable for individual quarters. As vacuum is increased, the distending forces are distributed throughout the unfolding dermis until an elastic limit and maximal CA is reached. The skin on the exterior of the teat end also likely achieves maximum distention under these

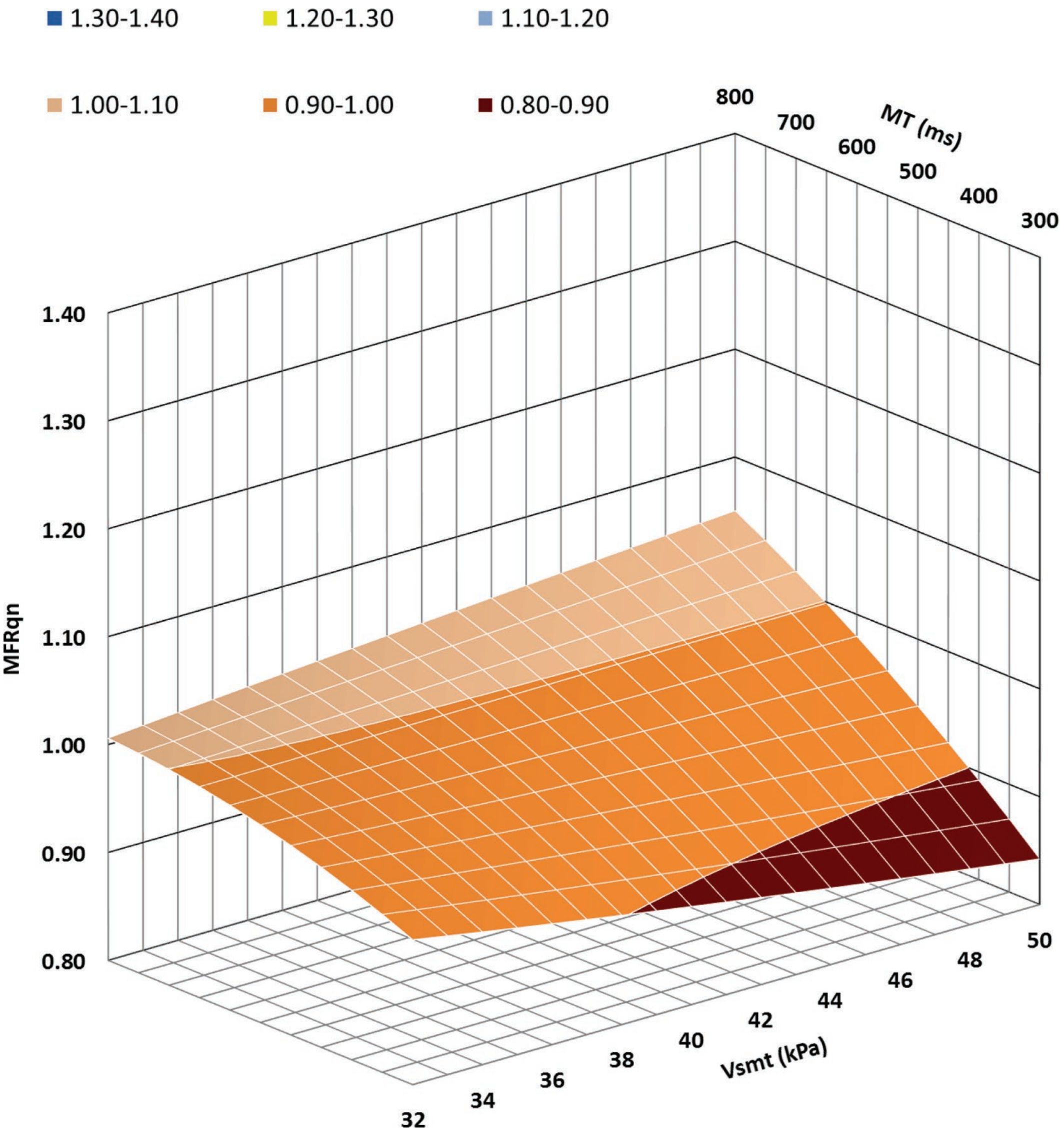

Figure 7. Quarter-normalized milk flow rate (MFRn, dimensionless fraction of quarter-average milk flow rate for all treatments) response to short milk tube vacuum (Vsmt) and milk-phase time (MT) for a low-compression liner (liner J, overpressure = 0.0 kPa) with rest-phase time held constant at 400 ms. Color version available online.

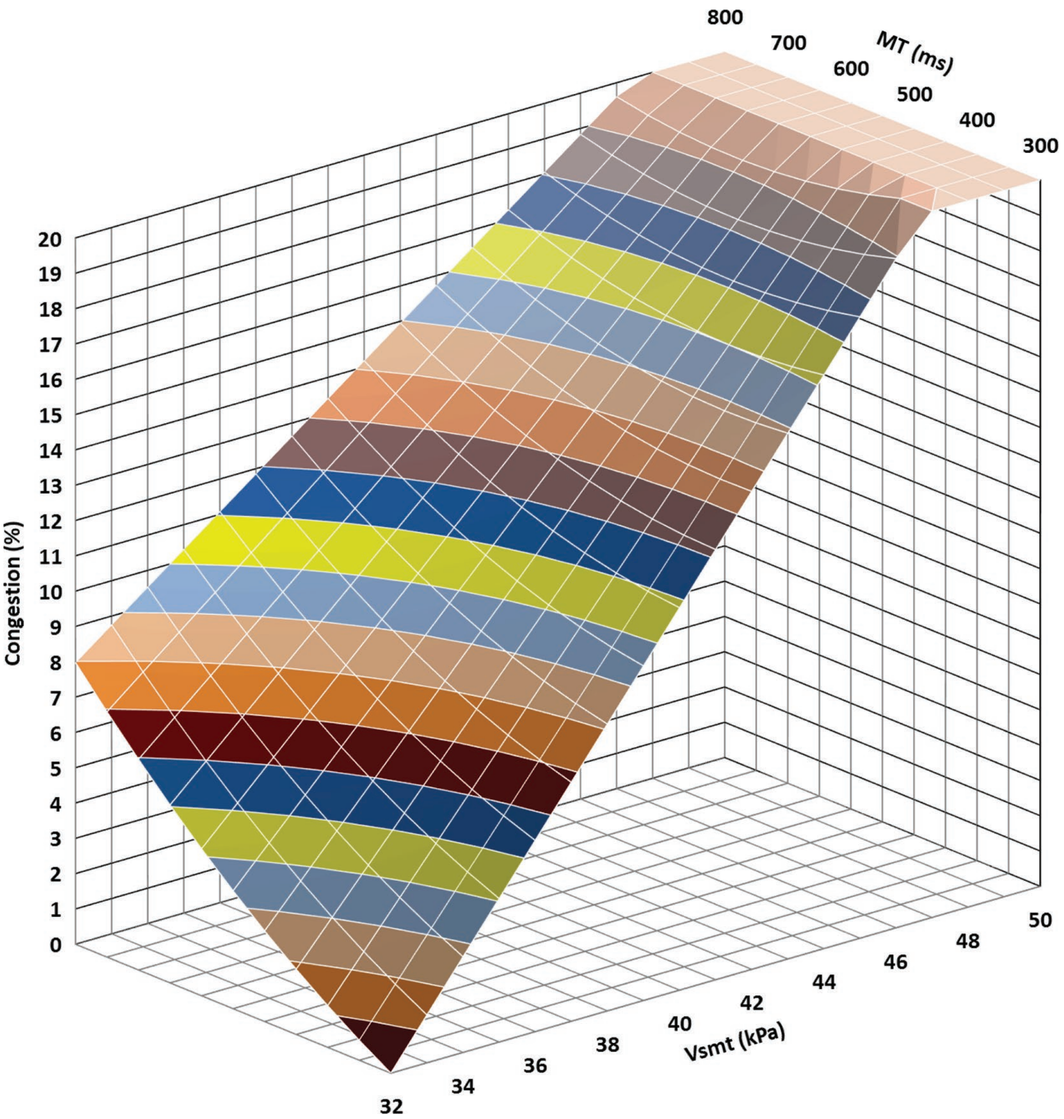

Figure 8. Teat-end congestion (change from maximum quarter-normalized teat canal cross sectional area) response to short milk tube vacuum (Vsmt) and milk-phase time (MT) for a low-compression liner (liner J, overpressure = 0.0 kPa) with rest-phase time held constant at 400 ms. Color version available online.

conditions. A decrease in CA results because of congestion of the soft tissues surrounding the teat canal that are constrained by the fully distended outer wall of the teat end. In our response surfaces, the minimum congestion (maximum CA) represents the combination of Vsmt, MT, OP, and Vmpc, where each individual teat CA is the largest. This generally occurred at the lowest Vsmt and MT, except for the highest compression liners (F, Figure 4), for which teat compression may increase more with increasing pressure difference across the liner (increasing Vsmt). For an individual liner, OP was shown to increase as Vs increased (Bade et al., 2007; Mein and Reinemann, 2007).

The examples of medium- (G, Figure 6) and high-compression liners (F, Figure 4) have a similar range of teat-end congestion of approximately 10%, whereas the low-compression liner (J, Figure 8) had teat-end congestion of approximately twice this value. For the low-compression liner, any increase in either Vsmt (from 32 kPa) or MT (from 300ms) increased congestion, unlike the examples of medium- and high-compression liners. Although increasing liner OP can result in both increased MFR and reduced teat-end congestion, several authors have reported that the risk of teat-end hyperkeratosis increases as liner compression is increased, (Mein et al., 2003; Zucali et al., 2008, Mein and Reinemann, 2009; Kochman and Little, 2010). The predicted risk of teat-end hyperkeratosis was thus lowest for the low-compression liner.

Our experiment is the first time that a central composite design with repeating center points and different treatments applied within a single milking at the quarter level to assess MFR has been reported. Repeating the center points, and randomizing treatment order, accounted for changes to each individual teat during the course of 1 milking. A single estimate of liner OP was used for each liner used in our experiment. This single OP estimate per liner was used to calculate MT for each treatment. Leonardi et al., (2015) showed a standard error of 1.5 kPa for OP estimates across quarters as well as a 2.6 kPa reduction in OP as milking progresses. Liner OP was also shown to increase as Vs increased (Bade et al., 2007). We postulated that the accuracy of CA estimates would be improved if we could be account for sources of variability in OP.

CONCLUSIONS

The methods presented in this paper, MFR, MT, Vmpc, and Vsmt measurement at the quarter level, in addition to the use of a central composite experimental design applied during a single milking session, provided sufficient precision to estimate the effects of vacuum, pulsation, and liner compression on the effective teat canal cross-sectional area (as an indicator of teat-end congestion) during the peak flow period of milking. Liner compression (as indicated by OP), teat-end vacuum (Vsmt), vacuum in the liner mouthpiece (Vmpc), and the milk-phase time (MT), plus their interactions, are all important predictors of MFR and teat-end congestion during the peak milk flow period of milking. This experiment used a constant rest-phase time so that MT was directly related to the true milk ratio of pulsation. Increasing Vsmt and MT increased MFR and reduced CA (indicative of increased teat-end congestion). Increasing Vmpc also acts to reduce CA and MFR. Increasing liner OP reduces the effects of teat-end congestion, resulting in increased MFR and increased CA at high levels of Vsmt and MT. These results provide a better understanding of the balance between milking speed and milking gentleness.

ACKNOWLEDGMENTS

Milk harvesting research conducted at the University of Wisconsin–Madison is supported by Avon Dairy Solutions (Melksham, United Kingdom), Dairy Australia (Melbourne, Australia), and Teagasc (Fermoy, Co. Cork, Ireland).

REFERENCES

Ambord, S., and R. M. Bruckmaier. 2009. Milk flow-controlled changes of pulsation ratio and pulsation rate affect milking characteristics in dairy cows. J. Dairy Res. 76:272–277.

Ambord, S., and R. M. Bruckmaier. 2010. Milk flow-dependent vacuum loss in high-line milking systems: effects on milking characteristics and teat tissue condition. J. Dairy Sci. 93:3588–3594.

Bade, R. D., D. J. Reinemann, and G. A. Mein. 2007. Sources of variability in compressive load applied to bovine teats. Pages 212–213 in 46th Natl. Mastitis Counc. Ann. Mtg. Proc., San Antonio, TX. Natl. Mastitis Counc. Inc., Madison, WI.

Bade, R. D., D. J. Reinemann, M. Zucali, P. L. Ruegg, and P. D. Thompson. 2009. Interactions of vacuum, b-phase duration, and liner compression on milk flow rates in dairy cows. J. Dairy Sci. 92:913–921.

Box, G. E. P., and K. B. Wilson. 1951. On the experimental attainment of optimum conditions. R. Stat. Soc. B (Methodol.) 13:1–38.

Brown, G. 2002. The history of the Darcy-Weisbach equation for pipe flow resistance. Pages 34–43 in Environmental and Water Resources History. American Society of Civil Engineers, Reston. VA.

Bruckmaier, R. M., and J. W. Blum. 1996. Simultaneous recording of oxytocin release, milk ejection and milk flow during milking of dairy cows with and without prestimulation. J. Dairy Res. 63:201–208.

Bruckmaier, R. M., M. Weinfurtner, and D. Weiss. 2004. Teat anatomy and teat canal closure: Relationship with milk flow. Pages 132–134 in 43rd Natl. Mastitis Counc. Ann. Mtg. Proc., Charlotte, NC. Natl. Mastitis Counc. Inc., Madison, WI.

Butler, M. C., J. E. Hillerton, and R. J. Grindal. 1992. The control of milk flow through the teats of dairy cows. J. Dairy Sci. 75:1019–1024.

Gleeson, D. E., E. J. O'Callaghan, and M. V. Rath. 2003. Effect of vacuum level on bovine teat-tissue and milking characteristics. Ir. J. Agric. Food Res. 42:205–211.

Gleeson, D. E., E. J. O'Callaghan, and M. V. Rath. 2004. Effect of liner design, pulsator setting, and vacuum level on bovine teat tissue changes and milking characteristics as measured by ultrasonography. Ir. Vet. J. 57:289–296.

Grindal, R. J., and J. E. Hillerton. 1991. Influence of milk flow rate on new intramammary infection in dairy cows. J. Dairy Res. 58:263–268.

Hamann, J., and G. A. Mein. 1988. Responses of the bovine teat to machine milking: measurement of changes in thickness of the teat apex. J. Dairy Res. 55:331–338.

Hamann, J., and G. A. Mein. 1996. Teat thickness changes may provide biological test for effective pulsation. J. Dairy Res. 63:179–189.

Hamann, J., G. A. Mein, and S. Wetzel. 1993. Teat tissue reactions to milking: Effects of vacuum level. J. Dairy Sci. 76:1040–1046.

Kochman, A., and S. Little. 2010. The effect of over-pressure on teat-end condition. Pages 218–219 in 48th Natl. Mastitis Counc. Ann. Mtg. Proc., Albuquerque, NM. Natl. Mastitis Counc. Inc., Madison, WI.

Leonardi, S., J. F. Penry, F. M. Tangorra, P. D. Thompson, and D. J. Reinemann. 2015. Methods of estimating liner compression. J. Dairy Sci. 98:6905–6912.

Mein, G. A., and D. J. Reinemann. 2007. Making the most of machine on time: What happens when the cups are on? Pages 18–30 in 46th Natl. Mastitis Counc. Ann. Mtg. Proc., San Antonio, TX. Natl. Mastitis Counc. Inc., Madison, WI.

Mein, G. A., and D. J. Reinemann. 2009. Biomechanics of Milking: Teat-Liner Interactions 2009. ASABE Annual International Meeting Proc., Reno, Nevada, 2009. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Mein, G. A., D. J. Reinemann, I. Ohnstad, and E. J. O' Callaghan. 2004. 100 years with liners and pulsators: Where the rubber meets the teat and what happens to milking characteristics. Bull. Int. Dairy Fed. 388:28–34.

Mein, G. A., D. M. Williams, and C. C. Thiel. 1987. Compressive load applied by the teatcup liner to the bovine teat. J. Dairy Res. 54:327–337.

Mein, G. A., D. M. D. Williams, and D. J. Reinemann. 2003. Effects of milking on teat-end hyperkeratosis: 1. Mechanical forces applied by the teatcup liner and responses of the teat. Pages 114–123 in 42nd Natl. Mastitis Counc. Ann. Mtg. Proc., Fort Worth, TX. Natl. Mastitis Counc. Inc., Madison, WI.

Moody, L. F. 1944. Friction factors for pipe flow. Trans. ASME 66:671–684.

O'Callaghan, E. J., and D. E. Gleeson. 2004. A note on the effects of teat-end vacuum on milking characteristics. Ir. J. Agric. Food Res. 43:265–269.

Paulrud, C. O. 2005. Basic concepts of the bovine teat canal. Vet. Res. Commun. 29:215–245.

Reinemann, D. G. S., P. D. Thompson, and I. Ohnstadt. 2013. Exploring the role of liner shape, dimensions and venting on liner performance. Pages 64–70 in 52nd Natl. Mastitis Counc. Ann. Mtg. Proc., San Diego, CA. Natl. Mastitis Counc. Inc., Madison, WI.

Reinemann, D. J., and G. A. Mein. 2010. Review of milking biomechanics research. Pages 436–443 in Proc. IDF Mastitis Conference 2010, Christchurch, New Zealand. Int. Dairy Fed., Brussels, Belgium.

Upton, J., J. F. Penry, M. D. Rasmussen, P. D. Thompson, and D. J. Reinemann. 2016b. Effect of pulsation rest phase duration on teat end congestion. J. Dairy Sci. 99:3958–3965.

Upton, J., D. J. Reinemann, J. F. Penry, and P. D. Thompson. 2016a. A quarter milking analysis device—Development and demonstration. Biosyst. Eng. 147:259–264.

Williams, D. M., and G. A. Mein. 1986. The bovine teat canal: Information from measurement of velocity of milk flow from the teat. J. Dairy Res. 53:179–185.

Williams, D. M., G. A. Mein, and M. R. Brown. 1981. Biological responses of the bovine teat to milking: Information from measurements of milk flow-rate within single pulsation cycles. J. Dairy Res. 48:7–21.

Zucali, M., D. J. Reinemann, R. D. Bade, and A. Tamburini. 2008. Effects of Liner Compression on Teat-End Hyperkeratosis. Paper No. 083798, Written for presentation at the 2008 ASABE Annual International Meeting. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

APPENDIX A: DERIVATION OF TEAT CANAL CROSS-SECTIONAL AREA ESTIMATE

The flow of milk through the teat canal was modeled as incompressible fluid flow through a tube accounting for frictional losses using the Darcy-Wiesback equation (Brown, 2002)

$$\Delta p = f_D \times L/D \times \rho/2 \times u^2, \quad [1]$$

where Δp = pressure difference across the teat canal (Pa) taken as the sum of the short milk tube vacuum (Vsmt) and the positive pressure in the teat sinus (4.5 kPa based on Bruckmaier and Blum, 1996); f_D = Darcy friction factor 0.08 (dimensionless), from the Moody diagram (Moody, 1944) for turbulent flow in a rough pipe; L/D = length-to-diameter ratio of the teat canal (dimensionless) taken as 5.0, a constant value for an individual teat canal assuming a length of 10 mm from Gleeson et al. (2003), and teat canal diameter (D) of 2 mm; ρ = milk density = 1,030 kg/m^3; and u = milk velocity (m/s), which can be expressed as u = MFR/ρ/CA, where MFR is the mass flow rate of milk (kg/min), ρ is milk density (kg/m^3) and CA is the cross-sectional area of the teat canal (m^2).

By combining f_D and L/D into a single constant and making substitutions for pressure and velocity, equation 1 can be written as

$$\text{MFR} = \alpha \times \text{CA} \times (V_{smt} + 4.5)^{1/2}. \quad [2]$$

The right-hand side of equation 2 is then multiplied by the milk fraction (MF), to adjust MFR for the fraction of the pulsation cycle during which milk is flowing and units adjusted to yield the final predictive equation

$$\text{CA} = \alpha \times \text{MFR} \times \text{MF}^{-1} \times (\text{Vsmt} + 4.5)^{-1/2}, \quad [3]$$

where CA = teat canal cross sectional area (mm^2); α = 14.4, assumed to be constant for an individual teat canal; and Vsmt = short milk tube or teat-end vacuum (kPa).