J. Dairy Sci. 100:821–827
https://doi.org/10.3168/jds.2016-11533

Estimating teat canal cross-sectional area to determine the effects of teat-end and mouthpiece chamber vacuum on teat congestion

J. F. Penry,*[1] J. Upton,† G. A. Mein,‡ M. D. Rasmussen,§ I. Ohnstad,# P. D. Thompson,‖ and D. J. Reinemann‖
*Department of Dairy Science, University of Wisconsin-Madison, Madison 53705
†Animal and Grassland Research and Innovation Centre, Teagasc Moorepark Fermoy, Co. Cork, Ireland P61P302
‡Scientific consultant, Werribee South, Australia 3030
§Department of Engineering, Aarhus University, Denmark, 8000
#The Dairy Group, Taunton, United Kingdom TA12PX
‖Department of Biological Systems Engineering, University of Wisconsin-Madison, Madison 53705

ABSTRACT

The primary objective of this experiment was to assess the effect of mouthpiece chamber vacuum on teat-end congestion. The secondary objective was to assess the interactive effects of mouthpiece chamber vacuum with teat-end vacuum and pulsation setting on teat-end congestion. The influence of system vacuum, pulsation settings, mouthpiece chamber vacuum, and teat-end vacuum on teat-end congestion were tested in a 2 × 2 factorial design. The low-risk conditions for teat-end congestion (TEL) were 40 kPa system vacuum (Vs) and 400-ms pulsation b-phase. The high-risk conditions for teat-end congestion (TEH) were 49 kPa Vs and 700-ms b-phase. The low-risk condition for teat-barrel congestion (TBL) was created by venting the liner mouthpiece chamber to atmosphere. In the high-risk condition for teat-barrel congestion (TBH) the mouthpiece chamber was connected to short milk tube vacuum. Eight cows (32 quarters) were used in the experiment conducted during 0400 h milkings. All cows received all treatments over the entire experimental period. Teatcups were removed after 150 s for all treatments to standardize the exposure period. Calculated teat canal cross-sectional area (CA) was used to assess congestion of teat tissue. The main effect of the teat-end treatment was a reduction in CA of 9.9% between TEL and TEH conditions, for both levels of teat-barrel congestion risk. The main effect of the teat-barrel treatment was remarkably similar, with a decrease of 9.7% in CA between TBL and TBH conditions for both levels of teat-end congestion risk. No interaction between treatments was detected, hence the main effects are additive. The most aggressive of the 4 treatment combinations (TEH plus TBH) had a CA estimate 20% smaller than for the most gentle treatment combination (TEL plus TBL). The conditions designed to impair circulation in the teat barrel also had a deleterious effect on circulation at the teat end. This experiment highlights the importance of elevated mouthpiece chamber vacuum on teat-end congestion and resultant decreases in CA.
Key words: teat end, teat barrel, peak milk flow, vacuum, pulsation, congestion

INTRODUCTION

During milking the teat end can become swollen through congestion, which is an accumulation of fluid in the circulatory pathway, or a combination of congestion and edema. Edema is the accumulation of excess body fluid in the tissue interstitial space and is normally preceded by congestion (Reinemann, 2012). A single papillary artery supplies the teat; it courses through the middle layer of the teat wall and runs vertically and distal from the teat base. This artery passes inside a plexus of larger veins and the teat base venous ring. A superficial network of smaller arteries supplies the teat skin. Veins of the teat are large and thick walled, and they contain numerous valves directed toward the teat base. Arteries and veins are connected via a network of small capillaries throughout the skin and parenchymal tissue (Habel, 1989; Konig et al., 2004). Milk flows through the teat canal during the milking phase of pulsation because of the pressure difference across the teat end. Circulatory fluid also accumulates in the teat end at an increased rate due to reduced pressure within the tissues of the teat end. The function of pulsation in the teatcup is to provide liner compression to the teat end, which assists the return of blood and lymph flow through the veins and lymph ducts during milking (Williams et al., 1981; Hamann and Mein, 1996). No liner compression is applied to the teat-barrel wall through this process, and venous and lymphatic return is not assisted in the teat wall at the

Received May 30, 2016.
Accepted September 22, 2016.
[1]Corresponding author: penry@wisc.edu

level of the barrel except through forces applied at the teat end (Reinemann, 2012).

Teat-end congestion will reduce milk flow rate (**MFR**; Williams and Mein, 1986) and hence reduce milking speed. Congestion has also been associated with increased IMI (Mein et al., 1983; Zecconi et al., 1996). Teat-end congestion has previously been estimated in various ways, including use of a cutimeter (Hamann and Mein, 1988; Zecconi et al., 1992; Ambord and Bruckmaier, 2010), electronic calipers (Hamann et al., 1993), ultrasound (Gleeson et al., 2004; Bade et al., 2009), and optical methods (Zwertvaegher et al., 2013). Teat-end congestion can also be indirectly estimated by changes in the teat canal cross-sectional area (**CA**). During milking, the pressure difference created across the teat wall and teat end due to vacuum expands the teat end radially but within the confines of the open liner, while not exceeding the elastic limit of the epidermis and underlying connective tissue (Williams and Mein, 1982). The CA can be used as a biologically relevant indicator of congestion because the teat skin has limited ability to expand because of the forces generated by milking vacuum and congestion fluids compared with the inner parenchymal tissue. Once the teat skin has reached its elastic limit, parenchymal tissue in the teat-end region can only swell because of congestion through a decrease in the teat canal lumen CA (Williams and Mein, 1982). The CA can be estimated by the application of the Bernoulli theorem for liquid flow through a rough pipe from direct measurement of MFR, the total time milk is flowing during each pulsation cycle, and the pressure difference across the teat canal (Upton et al., 2016a).

Past research has demonstrated that an increase in teat-end vacuum can induce teat-end congestion (Hamann and Mein, 1988; Gleeson et al., 2004). Lengthening the b-phase duration has also been demonstrated to increase teat-end congestion when vacuum and liner compression are kept constant (Bade et al., 2009).

Teat-barrel congestion risk is driven by mouthpiece chamber vacuum (**Vmpc**), which is in turn affected by teat dimensions relative to liner dimensions (Gomez et al., 2011; Ronningen and Postma, 2012). Increased Vmpc has been shown to be associated with the formation of congestion in the teat barrel (Rasmussen, 1997; Reinemann et al., 2013). Because of the anatomical configuration of the teat circulatory system, particularly the venous system, we postulate that the pressure difference due to Vmpc that congests the teat-barrel might also congest the teat-end tissue through increased capillary pressure or constrictions in the venous pathways at any point in the teat barrel.

The primary objective of this experiment was to assess the effect of Vmpc on teat-end congestion. The secondary objective was to assess the interactive effects of Vmpc with teat-end vacuum and pulsation setting on teat-end congestion.

MATERIALS AND METHODS

A 2 × 2 factorial experimental design was used with treatment conditions designed for low or high risk of teat-end congestion (**TEL** and **TEH**, respectively) and low or high risk of teat-barrel congestion (**TBL** and **TBH**, respectively) as described in Table 1. A system vacuum of 49 kPa was chosen for the TEH condition to ensure a high probability of teat-end congestion. A triangular liner was used with the mouthpiece chamber (**MPC**) connected to either the short milk tube (**SMT**) or atmosphere. This liner had a measured mouthpiece diameter of 21 mm, mouthpiece depth of 35 mm, midbarrel diameter of 21 mm, and an overpressure (**OP**) of 9.8 kPa, indicating midrange liner compression. Eight cows (32 quarters) were used in the experiment, which was conducted during 0400 h milkings under IACUC-approved animal use protocol A005167. Cows were randomly assigned to the 4 treatments, with all cows receiving all treatments (2 × 2 factor combinations) over 4 d with the exception of one cow removed from the experiment because of behavior problems on d 3 and 4.

The experiment was carried out at the University of Wisconsin-Madison Dairy Cattle Center using a recently designed and constructed quarter milking analysis device (Mi4; Upton et al., 2016b). The design of Mi4 components for harvesting milk from a single quarter is described in Figure 1. Vacuum levels in the pulsation system, all short milk tubes (**Vsmt**), Vmpc, and milk weight harvested for each quarter were recorded at 1,000 Hz. The long milk hose connecting each teatcup to the milk collection tube was 16-mm internal diameter to reduce vacuum differences between Vsmt and system vacuum (**Vs**) due to friction. Teat lengths were recorded with a transparent ruler modified for this purpose before unit attachment on the first day of the experiment. All cows were prepared for milking with a teat disinfectant and wiped with a clean cloth before attachment after about 1 min according to the standard operating procedure of the parlor. Teatcups were applied for 150 s for all treatments to standardize the exposure period. This treatment time was chosen so that all quarters had a high probability of staying in the peak milk-flow period for the duration of each treatment allowing for assessment of teat-end congestion under the 4 treatment combinations. The d-phase duration for all treatments was 200 ms with the a-phase and c-phase each approximately 100 ms; the duration of the b-phase was held at either 400 or 700 ms by means of a purpose-built pulsator controller. This con-

Table 1. Treatment design and statistics for short milk tube vacuum (Vsmt), mouthpiece chamber vacuum (Vmpc), and milk flow rate (MFR)

				Mean (SD)		
Treatment[1]	b-phase duration[2] (ms)	System vacuum (kPa)	Mouthpiece chamber vent[3]	Vsmt (kPa)	Vmpc (kPa)	MFR (kg/min)
TEL TBL	400	40	A	37.1 (3.12)	1.8 (3.65)	1.09 (0.36)
TEH TBL	700	49	A	46.3 (2.24)	2.49 (4.52)	1.26 (0.45)
TEL TBH	400	40	SMT	37.6 (4.63)	37.3 (6.21)	0.96 (0.48)
TEH TBH	700	49	SMT	45.5 (2.24)	45.3 (2.63)	1.15 (0.52)

[1]TEL = teat-end congestion risk low; TEH = teat-end congestion risk high; TBL = teat-barrel congestion risk low; TBH = teat-barrel congestion risk high.

[2]The TEL treatments used a pulsation rate of 75 pulsations per minute and pulsator ratio of 62.5:37.5, whereas the TEH conditions used a pulsation rate of 54 pulsations per minute and pulsator ratio of 73:27 to keep the durations of other phases constant at 100 ms for the a phase, 100 ms for the c phase, and 200 ms for the d phase.

[3]Mouthpiece chamber vented to either atmosphere (A) or short milk tube (SMT). Note that 2 levels of average mouthpiece chamber vacuum were used for TBH.

trolled change in b-phase duration, while keeping other pulsation phases constant, was achieved by manipulation of both the pulsation rate and pulsator ratio. All treatments with TEL had a pulsation rate of 75 cycles/min and pulsator ratio of 62.5:37.5, while all treatments with TEH had a pulsation rate of 54 cycles/min and pulsator ratio of 73:27. Pulsation was provided in a 2 × 2 configuration with the same pulsation settings for front and rear quarters.

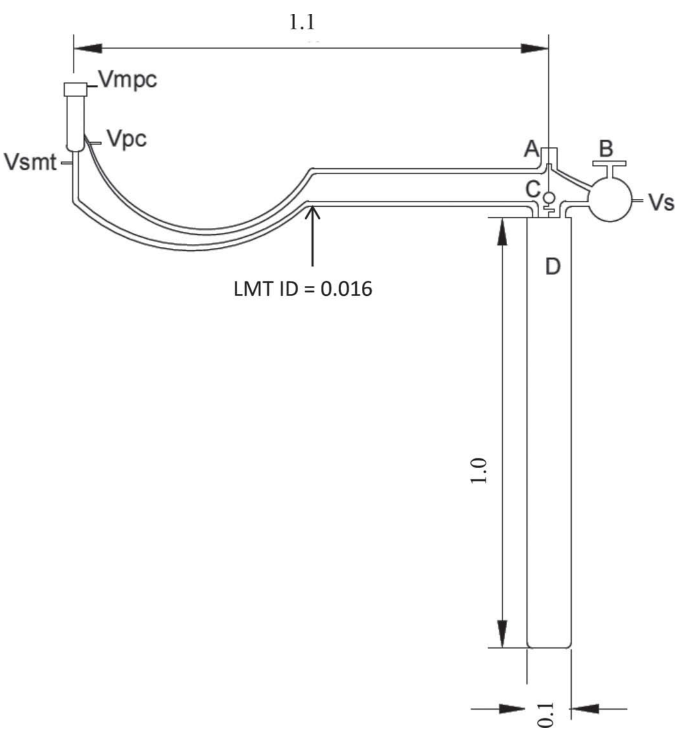

Figure 1. Diagram of one single quarter module of the Mi4 (Upton et al., 2016b) comprising a single teatcup connected to an individual milk collection chamber suspended on a load cell. A = pulsator; B = vacuum regulator; C = weigh cell; D = milk collection chamber; Vmpc = mouthpiece chamber vacuum measurement point; Vpc = pulsation chamber vacuum; Vsmt = short milk tube vacuum; Vs = system vacuum; LMT ID = long milk tube internal diameter. Dimensions in meters.

In this experimental design, the quarter was the experimental unit. Milk flow rate was calculated as the slope of a regression between milk mass and time over 5 complete pulsation cycles. Milk flow rate records for less than 15 s and more than 100 s of cups-on-time were removed from the analysis to ensure that all quarters were in the peak milk flow period of milking. Fifteen of 120 remaining quarter records were also removed from analysis because of vacuum sensor failure.

Pulsation chamber vacuum and liner OP was used to determine the ratio of the milk flow time period to total duration of one pulsation cycle (**MR**). During each 5 complete pulsation cycles, a mean short milk tube vacuum during the milking phase (**Vsmtm**) and MR were calculated. Also during each 5 complete pulsation cycles, CA was calculated as

$$\mathrm{CA} = \alpha \times \mathrm{Q} \times \mathrm{MR}^{-1} \times (\mathrm{Vsmtm} + 4{,}500)^{-1/2}, \quad [1]$$

where α is a constant of 28.4 $(\mathrm{kg/m^3})^{1/2}$, Vsmtm is the vacuum in the SMT (Pa) during the milking phase, Q is the volumetric flow rate ($\mathrm{m^3/s}$) of milk from the teat, and MR is the milk ratio (i.e., the fraction of the pulsation cycle during which milk is flowing). For a detailed derivation of Equation [1], see Upton et al. (2016a).

A mean CA for each quarter × treatment combination was calculated, and the result was used as the CA variable in the statistical model. The mean Vsmt, Vmpc, and MFR were likewise calculated for each quarter × treatment combination. The mean and standard deviation of Vsmt and Vmpc for each treatment described in Table 1 are based on measurements taken throughout the entire pulsation cycle from 15 s to 100 s of cups-on-time. An example of vacuum measurements from 1 teat over 5 complete pulsation cycles is described in Figure 2.

The SAS MIXED procedure (SAS 9.4, SAS Institute Inc., Cary, NC) was used to assess the main and interactive effects of teat-end congestion risk and teat-barrel congestion risk on CA. Teat-end congestion risk, teat-barrel congestion risk, cow, quarter, and day were declared class variables. The covariate teat length was declared a continuous variable. Cow and quarter within cow were declared as random effects with quarter within cow repeated. Covariance was modeled using the autoregressive (1) structure to account for day-to-day correlation between treatments within quarter. Day ($P = 0.411$), teat length ($P = 0.154$), and the interactive term for teat-end and teat-barrel congestion risk ($P = 0.410$) were dropped from the model because the terms were not significant. The final model was

$$\text{CA} = \text{teat-end congestion risk} + \text{teat-barrel congestion risk}. \quad [2]$$

RESULTS

The mean and standard deviation of Vsmt, Vmpc, and MFR for all treatments are summarized in Table 1. The TBH treatments had a mean Vmpc of 37.3 or 45.3 kPa, which was within 1 kPa of the mean Vsmt for each TBH condition, while TBL treatments had a mean Vmpc that was less than 3 kPa. The average teat

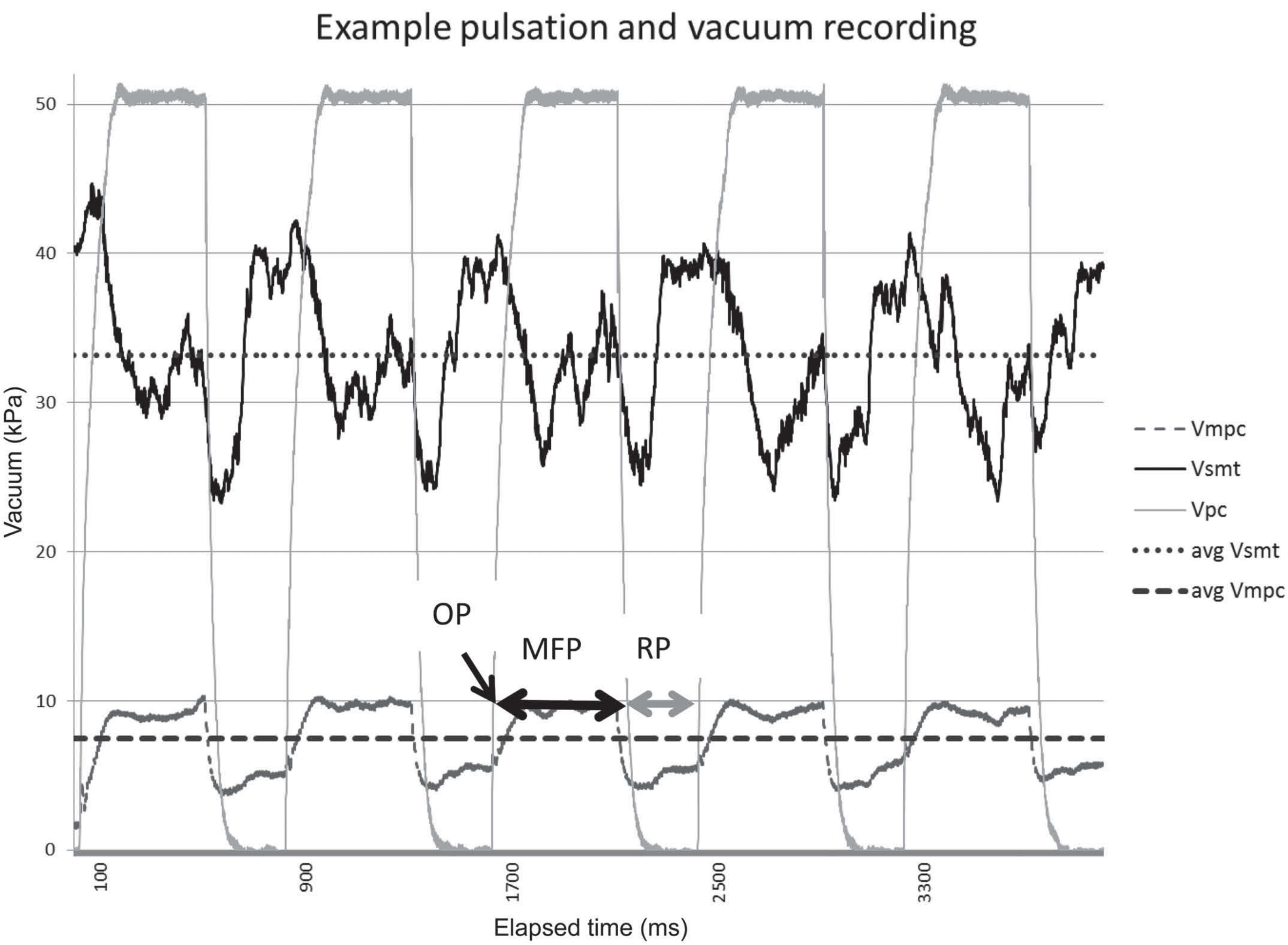

Figure 2. Example of 5-pulsation cycle vacuum measurements from cow with teat-end low congestion risk–teat-barrel low congestion risk treatment (TEL-TBL). Vmpc = mouthpiece chamber vacuum, teat no. 2; Vsmt = short milk tube vacuum, teat no. 2; Vpc = pulsation chamber vacuum; avg Vsmt = average short milk tube vacuum; avg Vmpc = average mouthpiece chamber vacuum; MFP = period of pulsation cycle designated as milk flow period; RP = period of pulsation cycle designated as rest period; OP = liner overpressure level (kPa).

Table 2. Mixed-model ANOVA

Effect	df	F-value	P-value
Teat-end congestion risk	1	6.37	0.017
Teat-barrel congestion risk	1	4.80	0.038

length in this experiment was 43.7 mm (SD 6.7 mm) with an average width of 24.8 mm (SD 2.7 mm).

Analysis of variance results for the mixed model are given in Table 2. The main effects of teat-end congestion risk and teat-barrel congestion risk were both significant, with P-values of 0.017 and 0.038, respectively. The final model solution is presented in Table 3 for teat-end congestion and teat-barrel congestion risk. The main effect size for teat-end congestion risk (TEL to TEH) was -0.32 mm^2 with an almost identical outcome for the main effect size for teat-barrel congestion risk of -0.31 mm^2 (TBL to TBH); both produced about a 10% decrease in CA. Because no interaction between congestion risk treatments was detected, the effects were additive, with the effect of teat-end congestion risk not dependent on the effect of teat-barrel congestion risk and vice versa. From the gentlest milking treatment combination applied (TEL plus TBL) to the most aggressive combination (TEH plus TBH), CA decreased by approximately 20% (Figure 3). The 2 TEL treatments had the smallest MFR because of a 9-kPa-lower milking vacuum than for the TEH treatments. With either the low- or high-risk conditions for teat-end congestion, going from the low- to high-risk condition for teat-barrel congestion resulted in an 8 to 10% decrease in MFR for the same teat-end vacuum and pulsation conditions.

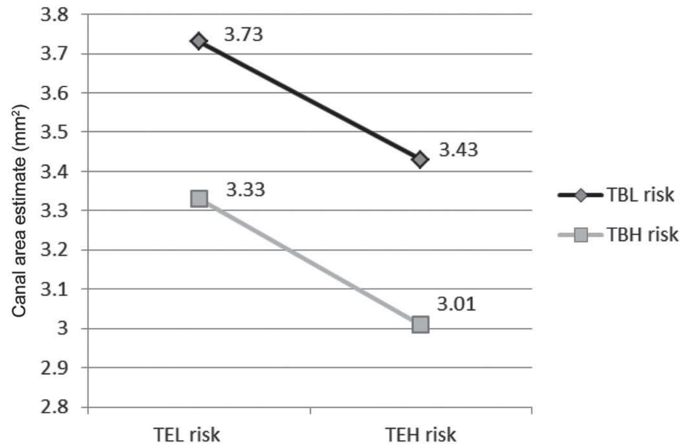

Figure 3. Model prediction for teat canal cross-section area estimate by treatment (mm^2) for low (TEL) or high (TEH) teat-end congestion risk and low (TBL) or high (TBH) teat-barrel congestion risk.

DISCUSSION

An increase in either Vs or b-phase duration increases the teat-end congestion risk. The results described in Table 1 indicate that the elevation of Vs from 40 to 49 kPa elevated Vsmt from approximately 38 kPa for the TEL treatments to 45 kPa for the TEH treatments. The resultant Vsmt was above the 36 to 42 kPa recommended for gentle milking (Mein and Reinemann, 2007). The b-phase duration in the TEH treatments was 700 ms compared with 400 ms in the TEL treatments. This 700-ms duration for the high-risk treatments was chosen in part because of previous findings in which MFR within a single pulsation cycle decreased after approximately 500 ms of b-phase due to vascular congestion of the teat end (Williams et al., 1981). The majority of teats in this experiment subjected to the TEH treatments showed visual and tactile signs of teat-end congestion, specifically skin color change and firmness. These visual observations immediately following teatcup removal indicate the 4 treatments reliably created conditions for low or high teat-end congestion.

Hamann and Mein (1996) found that increasing the b-phase had an effect similar to increasing Vs on congestion risk with pulsation ratios of 50:50, 70:30, and 80:20. The reduction in MFR observed at a pulsation ratio of 80:20 was ascribed to insufficient time for congestion to be relieved (Mein et al., 2004). When the shortened effective length of an experimental liner caused failure of pulsation (effectively elongating milking phase duration), teats were repeatedly observed as cyanotic and edematous (Mein et al., 1983).

In our experiment, risk of teat-barrel congestion was manipulated via Vmpc with the MPC connected to ei-

Table 3. Mixed model solution for main effects teat-end and teat-barrel congestion risk on canal area (CA)

Effect	CA estimate (mm^2) and SE: Low	CA estimate (mm^2) and SE: High	Effect size low to high condition (mm^2)	P-value[1]
Teat end	3.53[a] (0.39)	3.21[b] (0.39)	-0.32	0.017
Teat barrel	3.52[a] (0.39)	3.21[b] (0.39)	-0.31	0.038

[a,b]CA estimates within a row without a common superscript letter were significantly different at $P < 0.05$.
[1]Significance at $P < 0.05$.

ther atmosphere or Vsmt. During the TBH treatments, average Vmpc was within 1 kPa of average Vsmt (33 kPa or more in excess of the TBL condition average Vmpc; Table 1), and thus it was in excess of levels recommended for optimal udder health (10–30 kPa; Ronningen and Postma, 2012). Because of the <1 kPa difference between average Vsmt and Vmpc, vacuum in the MPC was also outside the recommendations of Rasmussen (1997), who suggested that Vmpc should ideally be 10 kPa below Vsmt during the peak flow period. The Vmpc levels for the TBL treatments were 1.80 to 2.49 kPa (mean). These levels are below the recommended level of 10 to 30 kPa (Ronningen and Postma, 2012), which was presumably associated with increased liner slip; however, the teatcups in this experiment were manually supported during each milking and no liner slips occurred. Distinct ringing of the teat barrel was noted for the majority of teats subjected to TBH treatments and not with the TBL treatments. This observation indicated that the risk for teat-barrel congestion was successfully altered through the chosen Vs, MPC venting, and b-phase duration parameters.

The risk of teat-barrel congestion is a function of vacuum level in the MPC. Reinemann et al. (2013) compared a liner vented in the MPC with nonvented liners and found the vented liners were 1.9 times less likely to induce barrel congestion. Increasing mouthpiece depth also raised Vmpc during the peak milk flow period, with Vmpc rising even further during the low milk flow period. The range of MPC depths in commercial liners is approximately 20 to 45 mm (Gomez et al., 2011), so the geometry of this section of the liner can differ between liners. Teat dimensions relative to the liner geometry influence Vmpc. Poor fit between the liner wall and teat skin or around the mouthpiece opening has been suggested to increase Vmpc (Borkhus and Ronningen, 2003; Ronningen and Postma, 2012). Our interpretation of liner fit is the relationship between MPC depth and teat length in addition to the relationship between liner midbore barrel diameter and teat-barrel width. These liner dimensions are described in ISO 3918 (ISO, 2007).

Average MFR differed by 29% across the 4 treatments, but the 2 lowest average MFR treatments were both combinations incorporating the TEL condition. This result was anticipated, given that Vs was 9 kPa lower and pulsation ratio was also lower for TEL versus TEH treatments. A similar decrease of between 9 and 10% in average MFR was seen with both TEL and TEH conditions when the risk of teat-barrel congestion was altered from low to high. From the Bernoulli theorem and with Vsmt being similar for each TEL or TEH condition, the change in average MFR resulting from changes in the risk of teat-barrel congestion could be attributed to changes in CA. With congestion in the teat barrel, venous return can be compromised thereby increasing capillary engorgement. This engorgement and the resultant increased capillary pressure, can in turn cause congestion in the teat end and reduce teat canal CA.

The decrease in CA with the high-risk treatments for teat-end congestion was approximately 10% or 0.32 mm^2, which is larger than the 0.12 mm^2 (4%) reported by Williams and Mein (1986) when they increased Vs from 40 to 50 kPa. It makes physiological sense for the high-risk teat-end congestion treatments to decrease CA through congestion and possibly edema. We are not able to directly relate the estimated change in CA with previously reported estimates of change in teat-end thickness (Hamann and Mein, 1988; Ambord and Bruckmaier, 2010; Zwertvaegher et al., 2013). A threshold of 5% as the maximum allowable teat-end thickness change was previously suggested (Hamann and Mein, 1996). Changes in dimension as measured on the outside of the teat end cannot necessarily be assumed to create the same proportional change near the teat canal.

Congestion in the teat end is the accumulation of blood in the circulatory system as a result of constrictions in the venous flow pathway. Our results indicate that milking conditions that induce teat-barrel congestion are capable of effecting a similar constriction in the venous pathway leading blood away from the teat end irrespective of the degree of swelling in the teat end produced in this experiment.

The size of the additive effects of teat-end and teat-barrel congestion are important to milking speed. These congestive effects were apparent during the peak milk flow period and would likely have been larger if milking was allowed to enter the low MFR period. Teat-barrel congestion can also reduce the completeness of milking because the connection between the teat sinus and udder cistern can be more easily occluded (Reinemann, 2012). Conditions that increase the risk of teat-barrel congestion in the absence of teat-end congestion risk can alter MFR during the peak flow period through a decrease in CA. This possibility is relevant in case of poor teat-liner fit and if wide-bore liners are used on small diameter teats because these scenarios contribute to an increase in Vmpc (Ronningen and Postma, 2012).

CONCLUSIONS

Milking conditions designed to induce teat-barrel congestion and impair circulatory pathways in the teat barrel reduced teat CA. The size of this effect was as large as the effect of milking conditions that produced teat-end congestion only. No interaction was found between vacuum conditions that may result in teat-end congestion and those that may cause teat-barrel congestion. Each treatment effect produced a 10% decrease in teat CA and commensurate change in MFR. Between the gentlest and most aggressive milking conditions applied in this experiment, a decrease of about 20% in CA was detected. The results of this experiment highlight the importance of maintaining low MPC vacuum levels during the peak milk flow period to enhance both milking speed and gentleness of milking.

ACKNOWLEDGMENTS

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

REFERENCES

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, 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.

Borkhus, M., and O. Ronningen. 2003. Factors affecting mouthpiece chamber vacuum in machine milking. J. Dairy Res. 70:283–288.

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.

Gomez, S. A., D. J. Reinemann, and P. D. Thompson. 2011. Predicting liner performance. Pages 121–122 in 50th Natl. Mastitis Counc. Ann. Mtg. Proc., Arlington, VA. Natl. Mastitis Counc. Inc., Madison, WI.

Habel, R. E. 1989. Guide to Dissection of Domestic Ruminants. 4th ed. R.E. Habel, Ithaca, NY.

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.

ISO. 2007. Milking machine installations—Vocabulary. ISO 3918:2007. International Organization for Standardization, Geneva, Switzerland.

Konig, H. E., H. Leibich, and H. Bragulla, eds. 2004. Veterinary Anatomy of Domestic Animals: Textbook and Colour Atlas. Schattauer, Stuttgart, Germany.

Mein, G. A., M. R. Brown, and D. M. Williams. 1983. Pulsation failure as a consequence of milking with short teatcup liners. J. Dairy Res. 50:249–258.

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., 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.

Rasmussen, M. D. 1997. The relationship between mouthpiece vacuum, teat condition and udder health. Pages 91–96 in 36th Natl. Mastitis Counc. Ann. Mtg. Proc., Albuquerque, NM. Natl. Mastitis Counc. Inc., Madison, WI.

Reinemann, D. J. 2012. The smart position on teat condition. Pages 124–131 in Proc. of the New Zealand Milk Quality Conference, Hamilton. Dairy New Zealand, Hamilton, New Zealand.

Reinemann, D. J., S. Gomez, 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.

Ronningen, O., and E. Postma. 2012. Classification of mouthpiece chamber vacuum records in milking-time tests. Pages 219–220 in 51st Natl. Mastitis Counc. Ann. Mtg. Proc., St. Pete Beach, FL. Natl. Mastitis Counc. Inc., Madison, WI.

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

Williams, D. M., and G. A. Mein. 1982. Review: Physical and physiological factors affecting milk flow rate from the bovine teat during machine milking. Pages 42–74 in Proc. Conf. Dairy Production from Pasture. K. L. Macmillan and V. K. Taufa, ed. New Zealand Society of Animal Production, Hamilton, New Zealand.

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.

Zecconi, A., V. Bronzo, R. Piccinini, P. Moroni, and G. Ruffo. 1996. Field study on the relationship between teat thickness changes and intramammary infections. J. Dairy Res. 63:361–368.

Zecconi, A., J. Hamann, V. Bronzo, and G. Ruffo. 1992. Machine-induced teat tissue reactions and infection risk in a dairy herd free from contagious mastitis pathogens. J. Dairy Res. 59:265–271.

Zwertvaegher, I., S. De Vliegher, B. Verbist, A. Van Nuffel, J. Baert, and S. Van Weyenberg. 2013. Short communication: Associations between teat dimensions and milking-induced changes in teat dimensions and quarter milk somatic cell counts in dairy cows. J. Dairy Sci. 96:1075–1080.