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Geometry of milk liners affects milking performance in dairy cows

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Abstract

The geometry of milk liners may affect milking performance and cow comfort as the milk liner is the only part of the milking machine that comes into contact with the teat. To determine the effect of alternative shape of milk liners we compared square (SQR) *vs.* the conventional round (RND) teat cup liner on milking performance and comfort of dairy cows. Treatment milk liners were randomly allocated to clusters within each side of the 12 a side double up-herringbone dairy shed in a complete randomised block design over two periods. Milking performance data from a total of 10 065 (late stage of lactation and once-a-day milking frequency, LATE) and 18 048 (early stage of lactation and twice-a-day milking frequency, EARLY) milking events were automatically recorded by a DeLaval milk meter, and separately analysed for LATE and EARLY, respectively. In EARLY, cow comfort behaviour was also recorded during afternoon milking sessions. Across the two study periods, average milk flow rate, milk flow rate during 0–15, 15–30 and 30–60 s after cluster attachment, and milk flow rate at cluster take-off were higher in SQR compared to RND treatment. Proportion of time in a milking session with low milk flow rate and duration of milking session were less in SQR compared to RND treatment. However, effect of geometry of milk liner on peak milk flow rate was inconsistent across the two-study periods. Peak milk flow rate was higher ($P < 0.001$) in SQR than RND in LATE, but higher ($P < 0.001$) in RND than SQR in EARLY. Stomping and kicking behaviours of cows were similar between treatments. Results of this study suggest that square milk liners potentially improve milking performance, without adverse effect on cow comfort compared to conventional round liners. Long-term, multi-site studies are required to confirm potential teat-end health benefits associated with square milk liners and further verify these results.

The primary aim of the milking machine is to harvest milk efficiently while ensuring animal health and comfort. The principle of milk harvest using a milking machine relies on creating a pressure difference between teat canal and teat-end by altering the pressure applied in teat and pulsation chambers (Williams *et al.*, 1981; Spencer, 2011). The milk harvest process occurs in two phases of the pulsation cycle: The open (milking) phase and the closed (resting) phase. During the milking phase, a vacuum level similar to that in the teat chamber is applied in the pulsation chamber, which opens the milk liners and allows the removal of milk from the teat. However, the vacuum applied during this phase causes the congestion of blood and other fluids within the teat tissues (Leonardi *et al.*, 2015). In the resting phase, atmospheric air is introduced into the pulsation chamber, increasing the pressure and causing the liner to collapse around the teat. This action prepares the teat canal for the next milking (open) phase by massaging the teat to remove accumulated fluids in teat-end tissues, enabling the harvesting of milk (Williams *et al.*, 1981; Bade *et al.*, 2009).

The teat cup liner is the only part of the milking machine that comes into contact with the udder. Its geometry may affect milking performance, teat-end health and cup slip in dairy cows (Schukken *et al.*, 2006; Kochman and Laney, 2009; Mein and Reinemann, 2009; Holst *et al.*, 2021). For instance, milk liners that result in a higher milk flow rate can also reduce the mechanical effect on the teat tissue due to shorter machine-on time (Besier and Bruckmaier, 2016; Odorčić *et al.*, 2019). Various options of milk liners, including round, triangular, oval and square shapes are available in the market. However, there is limited information regarding their specific effects on milking performance, making it challenging for farmers to select the optimal shape that suits their cows and machine settings (Penry *et al.*, 2016).

The geometry of the milk liner has been found to affect liner compression, which is the pressure applied to the teat tissues during closed or resting phase of the pulsation cycle, which in turn has an impact on teat condition, cow comfort and milk flow rate (Williams *et al.*, 1981; Mein *et al.*, 2013). Multi-sided milk liners have been suggested to apply more uniform compression around the teat compared to round milk liners due to their distinct shape (van der Tol *et al*., 2010; Sellner and Winona, 2019). It is suggested that this uniform compression reduces unnecessary stress and irritation on teat tissue, and may enhance cow comfort (Sellner and Winona, 2019). However, Holst *et al*. (2021) showed lower milk flow rate in triangular milk liners compared to round milk liners. Thus, selecting milk liners with the right geometry is crucial for achieving a balance between cow comfort and milking performance.

Ideally, achieving an adequate seal and friction between the liner and teat is vital for holding the teat cup in the correct position, particularly during the liner-opened phase, which is essential for achieving optimal milk flow rate (Holst *et al*., 2021). There are concerns that multi-sided (i.e. square or triangular) milk liners tend to experience premature slip of the milking cluster during the milking phase (Sellner, 2012). Consequently, various interventions have been implemented by manufacturers to address this limitation of multi-sided liners, aiming to prevent vacuum loss and potential tissue irritation (Alveby, 2016; Sellner and Winona, 2019). For example, some multi-sided liners incorporate a vent in the mouthpiece, which is expected to improve milk flow and reduce excessive vacuum on the teat by maintaining appropriate vacuum levels in the mouthpiece chamber (Grace and Novotny, 2011). Moreover, Grace and Novotny (2011) stated that multi-sided milk liners could offer more effective milking compared to round milk liners due to greater comfort for cows, and reduced teat-end health issues. However, most of the above are ideas, and research studies are required to confirm the effectiveness of the suggested interventions.

The potential benefits of multi-sided milk liners, such as those with a square geometry, require further confirmation and investigation. While several studies have compared triangular and round milk liners in terms of milking performance and teat-end condition (van der Tol *et al*., 2010; Difalco *et al*., 2011; Haeussermann *et al*., 2016; Penry *et al*., 2016, 2018; Holst *et al*., 2021), there is a scarcity of scientific evidence regarding the performance of square milk liners, although their effect on teat-end condition has been investigated (Schukken *et al*., 2006; Kochman and Laney, 2009). Overall, there is limited available data to assist farmers in selecting the most suitable and efficient type of liners considering milking performance and cow comfort. Therefore, the objective of this study was to compare the milking performance and comfort behaviour of dairy cows when using milking liners with two different geometries: square and round.

Materials and methods

Experimental site and design

The experiment was carried out over two periods at the Lincoln University Research Dairy Farm (LURDF; 43°38′20.6″S 172° 27′26.8″E) during the period from 8th March to 11th May 2022 (LATE), and 13th October to 30th November 2022 (EARLY). The experimental procedures were approved by the animal ethics committee, Lincoln University, New Zealand (AEC2022-40).

One week prior to the commencement of each period, new square (SQR) and round (RND) shape barrels (Skellerup Holdings Industries Limited, New Zealand) were randomly allocated to clusters within each side of a double up-herringbone dairy shed in a complete randomised block design. The commercially available treatment liners were made of the same rubber material (BfR compliant high-performance rubber), with similar liner stiffness of 55–66 Shore A and barrel wall thickness of 2.5 mm. The specifications and dimensions of square and round barrel milk liners are presented in Online Supplementary Table S1.

Milking machine and procedures

The milking system consisted of an automated smart DeLaval Del Pro FarmManager (calibrated in September 2022), which operated at high (60 cycles/min) and low (50 cycles/min) pulsation rate, and high (65:35) and low (30/70) pulsation ratio depending on the milk flow rate. The switch between pulsation ratios and rates was set at the start and end of the milking. At the beginning, the switch to a higher pulsation ratio and rate occurs if the milk flow is above the set low flow limit of 0.3 kg/min or after 60 s, whatever come first. At the end of milking, the switch back to the lower pulsation rate and ratio occurs if milk flow drops below the set low flow limit (0.3 kg/min), until the cluster is removed. The 12-aside double up-herringbone dairy shed operates automatic cup removers with a take-off limit of 0.3 kg/min. The post-milking time was 5 s from the moment the set low flow limit was reached and cups were removed. The system vacuum was set at the standard vacuum level of 43 kPa. The clusters were composed of a claw and four fully assembled cups, each featuring a ventilating opening (i.e. vent) in the claw.

The comparison was conducted over two periods. In LATE, average herd size of 165 Friesian × Jersey late lactating cows (150–200 d-in-milk) were milked once daily at a 24 h interval at 07:00 h. In EARLY, average herd size of 188 Friesian × Jersey early lactating cows (75–100 d-in-milk) were milked twice daily at consecutive 7- and 17-h intervals, (05:30 h and 13:30 h). The milking operation was conducted by one of three trained personnel. All operators followed a similar procedure of checking teats and quarters for any sign of infection or contamination before attaching the cluster to the teats. Any contamination was removed by washing the teats with cold flowing water and massaging if necessary to remove debris. At the end of milking all teats were sprayed with an iodine-based disinfectant.

In both periods cows were managed in sub-groups (12–40 cows per group) as part of other unrelated feeding trials. The cows in each sub-group had a similar age structure and grazed perennial ryegrass-white clover dominant pastures. Average daily milk yields were 11.1 ± 0.03 and 23.2 ± 0.05 kg/d/cow in LATE and EARLY, respectively. The order of milking was regularly changed, considering the approximate pasture area where each sub-group was grazing on that particular day. The change in group milking order may have resulted in cows being randomly rotated among clusters during different days of the study.

Data collection

Milk performance data were automatically recorded and downloaded daily from the DeLaval Del Pro FarmManager 5.5 (Version 2019.10.04.21). Data were not recorded from two afternoon milkings (5th and 24th November) during EARLY due to a technical failure. At each milking the DeLaval milk meter automatically recorded: average milk flow rate (overall average and during 0–15, 15–30, 30–60 and 60–120 s after cluster attachment); peak milk flow rate; take-off milk flow rate; proportion of time during a milking session when milk flow rate was less than 1.0 kg/min; milking duration (the time elapsed between cluster attachment and detachment) and milk yield per milking session.

Table 1. Average milking performance of two different milk liners; round barrel and square barrel in dairy cows milked once a day during late lactation (LATE)

Parameter	Treatment		*P*-value	SEM
	Round	Square		
Number of milking events	6.95	6.84	0.227	0.062
Average milk flow rate (kg/min)	1.95	2.20	<0.001	0.026
Milk flow rate 0–15 s [a] (kg/min)	0.023(0.1527)	0.038 (0.1957)	<0.001	0.002
Milk flow rate 15–30 s[b] (kg/min)	0.47 (−0.3316)	0.63 (−0.2013)	0.002	0.187
Milk flow rate 30–60 s[b] (kg/min)	0.23 (−0.6327)	0.27 (−0.5685)	<0.001	0.008
Milk flow rate 60–120 s (kg/min)	2.58	2.94	<0.001	0.034
Peak milk flow rate[a] (kg/min)	3.52 (0.5466)	3.93 (0.5946)	<0.001	0.006
Take off milk flow rate[a] (kg/min)	0.135 (−0.8691)	0.145 (−0.8375)	<0.001	0.002
Low milk flow rate[c] (%)	21.73 (1.337)	20.37 (1.309)	0.026	0.006
Duration of milking event[b] (seconds)	324 (2.511)	309 (2.49)	<0.001	0.003
Milk yield in first 2 min (kg)	3.57	4.07	<0.001	0.059
Average milk yield (kg/d)	10.60	11.25	<0.001	0.031

[a]Actual (square transformed) means are presented first and are followed by the square root transformed means in the parenthesis.
[b]Back log10 transformed means are presented with the log10 transformed means in the parenthesis.
[c]Proportion of time with low flow rate (<1.0 kg/min) in one milking session.

During EARLY, comfort behaviour observations were conducted twice weekly during the afternoon milking session. Four cows (two cows per treatment) were randomly selected for recording by a trained observer. Measurements included the number of stomping, kicking, kicking off the milking unit, urination and defecation events, (Kauppi, 2014; Phillips *et al.*, 2021; Prescott *et al.*, 1998; Rushen *et al.*, 1999), all per cow, as outlined in online Supplementary Table S2.

Statistical analysis

Each period was analysed separately using Genstat v19 statistical software (VSN International Ltd., Hemel Hempstead, UK). All variables were tested for normal distribution and those with skewed distributions were transformed before being analysed. All milking performance parameters were analysed using the restricted maximum likelihood modelling function (REML). Treatment (round *vs.* square milk liners) was considered as fixed factor, and cluster and cow nested within cluster were considered as random effect. In EARLY data analysis, milking time (morning or afternoon) and its interaction with the treatment were also included in the model as fixed factors. The means separation was carried out by Bonferroni test considering 0.05 as the confidence level.

Stomping and kicking behavioural data had skewed distribution and were square root transformed prior to analysis. The low occurrence of urination and kicking off the milking unit behaviours excluded these variables from analysis. Frequency data of stomping and kicking behaviour was analysed using REML considering treatment as the fixed factor and milking cluster and cow as the random factors.

Results

Data for LATE

The average daily number of milking events per cluster (6.9 ± 0.06) was similar between the SQR and RND treatments (Table 1). The average milk flow rate was 13% higher in the SQR than in the RND milk liners (Table 1, $P < 0.001$). Compared with RND liners, the effect of SQR liners was greatest at 0–15 s after cluster attachment with 65% higher flow rate. As milking progressed the difference in flow rate between liners declined, though SQR maintained a higher flow rate than RND liners throughout the milking (Table 1). In addition, peak and take-off milk flow rate were higher ($P < 0.001$) in the SQR compared to the RND treatment. Proportion of time in a milking session with low milk flow rate was less ($P < 0.05$) in the SQR compared with the RND milk liners. The duration of milking session was 5% shorter ($P < 0.001$) in SQR than RND milk liners (309 *vs.* 324 s/milking session). Milk yield at the end of the first two minutes after cluster attachment and average daily milk yield harvested per cluster (Table 1) were both higher ($P < 0.001$) in the SQR compared with the RND milk liners.

Data for EARLY

The average number of milking events per cluster was higher in RND compared to SQR milk liners during both morning (7.9 *vs.* 7.7 milking events) and afternoon (7.8 *vs.* 7.5 milking events) milking sessions, respectively ($P < 0.001$, Table 2). The average milk flow rate was higher in the SQR than the RND liners during both morning (2.34 *vs.* 2.30 kg/min) and afternoon (1.73 *vs.* 1.69 kg/min) milking session, respectively ($P < 0.001$, Table 2). There was a 27% (morning milking session) and 21% (afternoon milking session) higher flow rate from SQR than RND liners at 0–15 s after cluster attachment ($P < 0.001$, Table 2). However, this difference decreased over time, reaching an average difference of only 1% at 60–120 s ($P = 0.057$). This effect of square milk liners on milk flow rate was consistent across the morning and afternoon milking sessions with no interaction effect between treatment and milking time.

The peak milk flow rate was slightly but significantly higher in the RND compared to SQR milk liners in morning and afternoon milking sessions ($P = 0.01$, Table 2). Interaction effect between

Table 2. Average milking performance of two different milk liners; round barrel and square barrel in dairy cows milked twice a day (morning and afternoon) during early lactation (EARLY)

	Round		Square		*P*-value			
Parameter	Morning	Afternoon	Morning	Afternoon	Treatment	Milking session	Treatment × Milking session	SEM
Number of milking events	7.95	7.81	7.68	7.49	<0.001	<0.001	0.479	0.018
Average milk flow rate (kg/min)[1]	2.30 (0.3624)	1.69 (0.2281)	2.34 (0.3691)	1.73 (0.2371)	<0.001	<0.001	0.577	0.001
Milk flow rate 0–15 s (kg/min)[2]	0.022 (0.1496)	0.014 (0.1167)	0.028 (0.1684)	0.017 (0.1319)	<0.001	<0.001	0.554	0.001
Milk flow rate 15–30 s (kg/min)[1]	0.54 (−0.2661)	0.36 (0.4382)	0.67 (−0.1767)	0.44 (−0.3558)	<0.001	<0.001	0.586	0.003
Milk flow rate 30–60 s (kg/min)[1]	1.64 (0.2152)	0.64 (−0.1937)	1.69 (0.2288)	0.67 (−0.1723)	<0.001	<0.001	0.450	0.003
Milk flow rate 60–120 s (kg/min)	3.10	2.68	3.13	2.71	0.057	<0.001	0.889	0.01
Peak milk flow rate (kg/min)[1]	3.95 (0.5965)	3.61 (0.5572)	3.90 (0.5912)	3.57 (0.5523)	0.010	<0.001	0.928	0.001
Take off milk flow (kg/min)[1]	0.136 (−0.8656)[a]	0.157 (−0.8043)[b]	0.140 (−0.8545)[a]	0.176 (−0.7545)[c]	<0.001	<0.001	<0.001	0.002
Low milk flow rate (%)[3]	18.22	35.75	18.09	35.03	0.005	<0.001	0.087	0.086
Duration of milking event (seconds)[1]	388 (2.589)	261 (2.416)	378 (2.577)	251 (2.400)	<0.001	<0.001	0.239	0.001
Milk yield in first 2 min (kg)	4.27	3.18	4.35	3.29	<0.001	<0.001	0.560	0.011
Session milk yield (AM or PM) (kg/session)	15.45[c]	7.64[a]	15.03[b]	7.49[a]	<0.001	<0.001	0.011	0.025
Average milk yield (kg/d)	23.31		23.10		0.056	–	–	0.05

[1]Back log10 transformed means are presented with the log10 transformed means in the parenthesis.
[2]Actual (square transformed) means are presented first and are followed by the square root transformed means in the parenthesis.
[3]Proportion of time with low flow rate (<1.0 kg/min) in one milking session. Means within a row with different superscripts differ.

treatment and time of milking session was shown for milk flow rate at cluster take off. Milk flow rate at take-off was 12% higher in SQR than RND in the afternoon but similar between treatments during morning milking sessions. Regardless of milking session, proportion of time with low milk flow rate (<1.0 kg/min) in one milking session was less in the SQR than RND milk liners ($P < 0.01$, Table 2). Duration of milking session was reduced by 3 and 4% in the SQR compared with the RND milk liners during morning and afternoon milking sessions, respectively ($P < 0.001$, Table 2).

Milk yield at the end of the first two minutes after cluster attachment was 2 and 4% higher in the SQR compared with the RND milk liners during morning and afternoon milking sessions, respectively ($P < 0.001$, Table 2). There was an interaction effect ($P = 0.011$) between treatment and milking session (morning *vs.* afternoon), in which average milk yield per session was higher in RND than SQR milk liners in the morning but similar between treatments in the afternoon. Average daily milk yield per cluster was numerically (non-significantly) higher in RND than SQR milk liners.

Very few cows demonstrated signs of discomfort with no defecations, low numbers of urination (4.0 *vs.* 2.0 per milking event) and kicking off the cluster (1.0 *vs.* 0.0 per milking event) behaviour in RND and SQR treatments, respectively. The frequency of stomping behaviour of cows was similar ($P > 0.05$) between treatments (4.2 and 3.1, respectively for RND and SQR liners). The number of kicking events during milking was also not significantly different between RND or SQR milk liners (0.05 and 0.07, respectively).

Discussion

The consistently higher average milk flow rate of SQR compared with RND milk liners suggests that SQR liners may have improved friction between teat and milk liners. This improved friction probably reduced risk of liner climbing the teat (i.e. less teat tissue being sucked into the liner), increasing flow of milk from the teat (Mein *et al*., 1973; Williams *et al*., 1981; Holst *et al*., 2021). Borkhus and Rønningen (2003) reported that during milking (liner open) phase, the pressure difference between teat chamber and teat cistern creates a pressure gradient that extends the teat against the liner. The friction between the teat and the milk liner is crucial in maintaining the teat cup in a specific position, preventing the liner from climbing up the teat (Holst *et al*., 2021). The climbing of the teat cup, which in some cases could be observed by the development of a circular ring at the base of teat (Newman *et al*., 1991), can hinder milk flow by closing milk passage between gland and teat cistern (Mein *et al*., 1973; Holst *et al*., 2021). In addition, vacuum levels in the mouthpiece, and thus possibility of 'liner climbing the teat' increase with poor friction and seal between teat and liners (Holst *et al*., 2021). While the higher milk flow rate in SQR compared to RND liners suggests

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improved friction between SQR liners and the teat, further research is required on the effect of SQR liners on mouthpiece pressure.

Alternatively, the improved flow rate in this study possibly arises from better liner compression during the resting (liner closed) phase in the SQR compared to RND liners. Increased liner compression has been associated with increased milk flow rate (Williams *et al.*, 1981) and increased peak milk flow rate (Bade *et al.*, 2009). Improved liner compression during the resting phase of pulsation cycle results in an increased teat canal diameter at the start of the subsequent liners open phase. This is achieved through effective displacement of fluid congested in the teat tissues during the milking phase (Williams *et al.*, 1981). However, liner collapse pattern during the resting phase differs based on the liner shapes. For instance, triangular liners tend to collapse in three spots, while round and square milk liners collapse in two and four spots, respectively (van der Tol *et al.*, 2010). Liners that apply uniform pressure around the teat (i.e. square liners) were suggested to exert optimal compression (van der Tol *et al.*, 2010). Thus, our SQR liners may have provided better liner compression compared to RND liners, resulting in higher milk flow rate.

Our results showed that the pattern of milk flow leading to the improved average milk flow rate in SQR compared to RND liners was mainly driven by the higher milk flow at the start of the milking. Average milk flow rate during specific time intervals (0–15 s, 15–30 s, 30–60 s, and 60–120 s) after cluster attachment was consistently higher (but not always significantly, 60–120 s in EARLY; $P = 0.057$) in SQR milk liners compared to RND milk liners. According to the milking system settings, the transition to a higher pulsation rate and ratio was set to occur at a flow rate of 0.3 kg/min. The flow rate during the first 15–30 s of milking was significantly greater in SQR than in RND, exceeding the 0.3 kg/min threshold for both liners. Thus, the SQR milk liners could have switched to the higher pulsation ratio and rate earlier than the RND liners. To the best of our knowledge, no studies have examined milk flow rate in milk liners with square geometry, but a few have investigated this aspect in milk liners with triangular geometry (Penry *et al.*, 2016; Holst *et al.*, 2021). Holst *et al.* (2021) found that triangular milk liners resulted in lower milk flow rate and milk yield after one, two and three minutes of cluster attachment compared to round milk liners. They reported a higher vacuum level in the teat chamber and a lower vacuum level in the mouthpiece chamber with round milk liners, suggesting that round milk liners provided better friction and seal between the teat and milk liners compared to the triangular milk liners. It is possible that square liners, like those used in this study, offer superior geometry compared to the triangular ones used by Holst *et al.* (2021), resulting in improved friction between teat and milk liners and overall milking performance.

The higher average milk flow rate observed in SQR compared to RND milk liners reduced milking duration by 5% in LATE, and 3 and 4% in morning and afternoon milking sessions in EARLY. The reduced milking duration with SQR liners could have significant implications for decreasing overall milking time, especially for large herds milked in herringbone milking parlours. The milking of cows requires a substantial amount of labour hours, accounting for approximately 30–34% of annual labour hours in pasture-based systems (Deming *et al.*, 2018) and 50% of the weekly standard labour hours during peak production (Edwards *et al.*, 2020). Therefore, using square geometry milk liners may help reduce the labour requirements associated with milking. Another advantage of the reduced milking duration is the potential for improved teat health. Prolonged machine-on time has been associated with increased mechanical impact on teat tissue (Besier *et al.*, 2016; Stauffer *et al.*, 2020), which can potentially contribute to a higher incidence of hyperkeratosis (Neijenhuis *et al.*, 2000; Mein *et al.*, 2001) and increase the risk of teat lesions (Farnsworth, 1995). Although long-term teat health was not monitored in this study, the shorter milking duration associated with the SQR milk liners suggests a potential for fewer teat-end health conditions compared to RND milk liners. Further research is warranted to investigate the long-term effects of milk liner geometry on teat-end health and, potentially, somatic cell counts.

In this study, SQR milk liners showed a lower proportion of time with a low milk flow rate (<1 kg/min) compared to RND milk liners, implying potential additional benefits for teat health, as reported by Mein *et al.* (2001), Schukken *et al.* (2006) and Nørstebø *et al.* (2018). However, long-term effect of square milk liners on teat-end health is yet to be confirmed. The frequency of stomping and kicking behaviour observed in this study was similar between cows milked with either SQR or RND milk liners. This suggests that the geometry of the milk liners used in this study (square *vs.* round) did not affect cow comfort, although long-term study is required to confirm these results. Further multi-site studies encompassing different milking parlour settings, different breeds and cows with different production levels would provide a better understanding on the effect of square milk liners on cow health and comfort.

This study has certain limitations and efforts have been made to overcome those. In the experimental design used in this study, cows were randomly milked within each cluster treatment. However, the established milking order and/or potential preference for one side of the milking parlour (Varlyakov *et al.*, 2011) may have introduced individual cow effects or biased the results. To address this issue, both cluster and cow within cluster were included as a random effect in the statistical model. This approach accounts for variability among individual cows and reduces the impact of individual differences on the overall results. Additionally, the milking order of herds was regularly changed which will have minimised individual cow influence. Furthermore, treatment milk liners were randomised at the beginning of each study period to further reduce bias. However, it is important to note that in EARLY, there was a difference in the average number of milking events per cluster between the SQR and RND treatments. This difference in milking events may have affected the results and potentially contributed to the discrepancies observed in milk yield and peak milk flow results between LATE and EARLY, particularly, if a high producing cow exhibited a preference for one treatment cluster. For future studies, adopting a crossover experimental design is recommended to minimise the influence of individual cow effects and further verify results from this study.

In conclusion, the present study demonstrated that square milk liners improve the average milk flow rate compared to round milk liners, resulting in reduced milking duration for cows milked with square milk liners. The reduced machine-on time when using square milk liners, as opposed to round ones, may contribute to improved teat health in the long-term. The frequency of stomping and kicking behaviour in cows milked by either square or round liners was similarly low, suggesting no adverse effects on cow comfort due to the milk liner shape. While square milk liners appear to enhance milking performance compared to round ones, future studies are required to investigate the long-term effects on teat-end health and further verify these results.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S002202992400027X

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References

Alveby N (2016) Teatcupliner with enhanced teat massage. United States Patent 9408367B2 (ed). USA.

Bade R, Reinemann D, Zucali M, Ruegg P and Thompson P (2009) Interactions of vacuum, b-phase duration, and liner compression on milk flow rates in dairy cows. *Journal of Dairy Science* **92**(3), 913–921.

Besier J and Bruckmaier RM (2016) Vacuum levels and milk-flow-dependent vacuum drops affect machine milking performance and teat condition in dairy cows. *Journal of Dairy Science* **99**, 3096–3102.

Besier J, Lind O and Bruckmaier RM (2016) Dynamics of teat-end vacuum during machine milking: types, causes and impacts on teat condition and udder health – a literature review. *Journal of Applied Animal Research* **44**, 263–272.

Borkhus M and Rønningen O (2003) Factors affecting mouthpiece chamber vacuum in machine milking. *Journal of Dairy Research* **70**, 283–288.

Deming J, Gleeson D, O'Dwyer T, Kinsella J and O'Brien B (2018) Measuring labor input on pasture-based dairy farms using a smartphone. *Journal of Dairy Science* **101**, 9527–9543.

Difalco A, Gambina M and Licitra G (2011) Round shaped liners vs. triangular shaped liner and their effect on the teat end condition in a dairy herd located in southeastern Sicily. In: NMC Annual Meeting Proceedings. New Mexico, USA.

Edwards JP, Kuhn-Sherlock B, Dela Rue BT and Eastwood CR (2020) Short communication: Technologies and milking practices that reduce hours of work and increase flexibility through milking efficiency in pasture-based dairy farm systems. *Journal of Dairy Science* **103**, 7172–7179.

Farnsworth RJ (1995) Observations on Teat Lesions. *Retrieved from the University of Minnesota Digital Conservancy*.

Grace PP and Novotny TP (2011) Mouthpiece-vented teat cup inflation. WO2011068609A2 IIPO (ed). USA.

Haeussermann A, Britten J, Britten A, Pahl C, Älveby N and Hartung E (2016) Effect of a multi-sided concave liner barrel design on thickness and roughness of teat-end hyperkeratosis. *Journal of Dairy Research* **83**, 188–195.

Holst GE, Adrion F, Umstätter C and Bruckmaier RM (2021) Type of teat cup liner and cluster ventilation affect vacuum conditions in the liner and milking performance in dairy cows. *Journal of Dairy Science* **104**, 4775–4786.

Kauppi JJ (2014) Dairy cow behaviour in relation to health, welfare and milking. Doctoral Dissertation, Department of Production Animal Medicine, Faculty of Veterinary Science, University of Helsinki, Finland.

Kochman AK and Laney C (2009) The effect of liner barrel shape on teat end condition. 48th Annual Meeting, National Mastitis Council, Charlotte, NC.

Leonardi S, Penry JF, Tangorra FM, Thompson PD and Reinemann DJ (2015) Methods of estimating liner compression. *Journal of Dairy Science* **98**, 6905–6912.

Mein GA and Reinemann DJ (2009) Biomechanics of milking: teat-liner interactions. American Society of Agricultural and Biological Engineers meeting paper (097438), Reno, Nevada.

Mein GA, Thiel CC, Westgarth DR and Fulford RJ (1973) Friction between the teat and teatcup liner during milking. *Journal of Dairy Research* **40**, 191–206.

Mein G, Neijenhuis F, Morgan W, Reinemann D, Hillerton E, Baines J, Ohnstad I, Rasmussen M, Timms L, Britt J, Farnsworth RND and Cook N (2001) Evaluation of Bovine Teat Condition in Commercial Dairy Herds: 1. Non-Infectious Factors. AABP-NMC International Symposium on Mastitis and Milk Quality, Vancouver, BC, Canada.

Mein G, Reinemann D and Thompson P (2013) Understanding the milking machine: the contribution of cyclic liner compression to effective pulsation. In: NMC Annual Meeting Proceedings. San Diego, California, USA.

Neijenhuis F, Barkema HW, Hogeveen H and Noordhuizen JPTM (2000) Classification and longitudinal examination of callused teat ends in dairy cows. *Journal of Dairy Science* **83**, 2795–2804.

Newman JA, Grindal RJ and Butler MC (1991) Influence of liner design on mouthpiece chamber vacuum during milking. *Journal of Dairy Research* **58**, 21–27.

Nørstebø H, Rachah A, Dalen G, Rønningen O, Whist AC and Reksen O (2018) Milk-flow data collected routinely in an automatic milking system: an alternative to milking-time testing in the management of teat-end condition?. *Acta Veterinaria Scandinavica* **60**, 2.

Odorčić M, Rasmussen MD, Paulrud CO and Bruckmaier RM (2019) Review: milking machine settings, teat condition and milking efficiency in dairy cows. *Animal: An International Journal of Animal Bioscience* **13**, 94–99.

Penry JF, Leonardi S, Upton J, Thompson PD and Reinemann DJ (2016) Assessing liner performance using on-farm milk meters. *Journal of Dairy Science* **99**, 6609–6618.

Penry JF, Upton J, Leonardi S, Thompson PD and Reinemann DJ (2018) A method for assessing teatcup liner performance during the peak milk flow period. *Journal of Dairy Science* **101**, 649–660.

Phillips HN, Sorge US and Heins BJ (2021) Effects of pre-parturient iodine teat dip applications on modulating aversive behaviors and mastitis in primiparous cows. *Animals* **11**, 2–13.

Prescott NB, Mottram TT and Webster AJF (1998) Effect of food type and location on the attendance to an automatic milking system by dairy cows and the effect of feeding during milking on their behaviour and milking characteristics. *Animal Science* **67**, 183–193.

Rushen J, de Passillé AMB and Munksgaard L (1999) Fear of people by cows and effects on milk yield, behavior, and heart rate at milking. *Journal of Dairy Science* **82**, 720–727.

Schukken Y, Petersson L and Rauch B (2006) Liners and teat end health. National Mastitis Council Annual meeting proceedings, Florida, USA.

Sellner DF (2012) Teat cupliner. United States Patent 8, 145 B2 (ed). USA.

Sellner DF and Winona MN (2019) Teat cup liner. European patent specification EP2192831B1 (ed).

Spencer SB (2011) Milking machines: principles and design. In Fuquay JW (ed.), *Encyclopedia of Dairy Sciences*. 2nd Edn. San Diego: Academic Press, pp. 941–951.

Stauffer C, Feierabend M and Bruckmaier RM (2020) Different vacuum levels, vacuum reduction during low milk flow, and different cluster detachment levels affect milking performance and teat condition in dairy cows. *Journal of Dairy Science* **103**, 9250–9260.

van der Tol PPJ, Schrader W and Aernouts B (2010) Pressure distribution at the teat–liner and teat–calf interfaces. *Journal of Dairy Science* **93**, 45–52.

Varlyakov I, Radev V, Slavov T and Grigorova N (2011) Behaviour of cows in milking parlour. *Agricultural Science and Technology* **3**, 107–111.

Williams DM, Mein GA and Brown MR (1981) Biological responses of the bovine teat to milking: information from measurements of milk flow-rate within single pulsation cycles. *Journal of Dairy Research* **48**, 7–21.