SURVEY OF LINER CHARACTERISTICS USED IN JAPAN

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Research

HIGHLIGHTS

- The vacuum during milking causes teat ends to suck into liners by 7 to 10 cm.
- Liner rubber is classified as hard or soft.
- Volume changes are greater in round liners than those of other shapes in the pulsation cycle.
- Non-round liners did not press completely during the closing phase.
- The liner shape had a greater effect on liner volume change than the material.

ABSTRACT. *A variety of liner shapes are used in the dairy industry in Japan, and it is not known which is optimal for maintaining teat-end condition, preventing mastitis, ensuring milk quality, and improving dairy cow and milking system performance. Liners can be generally classified into types based on their internal shape: round, round with ribs on the outside of the liner, triangular, clover-shaped, or square. In addition, liners can be characterized based on the position of the air vent. The optimal combination of air vent location and internal shape for the maintenance of good teat end condition has not been clarified. The aim of this study is to survey liners in Japan to determine the characteristics of liners currently in use. The depth to which the teat end is pulled into the liner during milking was investigated. An experimental vacuum device was fabricated to measure the touch-point and closure-point (the vacuum levels at which the opposite sides of the internal liner surface begin to touch, and the level at which the liner bore completely closes, respectively). In addition, the volume change of the pulsation chamber during the pulsator opening and closing phases was also investigated. The internal shape of the liner was molded when the liner was opened and closed, and the cross-sectional area was compared for each liner type. The findings showed that liner hardness could be characterized as being either soft or hard. The change in the bore volume of round liners during a pulsation cycle, i.e., between the pulsation opening phase and the closing phase, was larger than that observed with the other liners. The cross-sectional area of the molded shape tended to be wider for liners of other shapes than for round liners. This study investigated and compared the characteristics of various types of liners and found that the characteristics varied widely. It is not clear what kind of liner shape is best, and further research is needed.*

Keywords. *Liner internal shape, Overpressure, Pulsation, Teat end condition, Teat end position.*

We previously identified numerous problems with Japanese milking systems (Enokidani et al., 2019). The findings of that study showed that, compared to National Mastitis Council standards, the clear rate of milking systems in Japan is 21.6%. In a study on the effect of operating vacuum on dairy cow performance and teat tissue damage, Besier and Bruckmaier (2016) reported that the claw vacuum during milking was more important than the operating vacuum for improving dairy cow performance, and that removing the liner early was important for reducing teat damage.

Rasmussen and Madsen (2000) investigated milking system settings and teat end hyperkeratosis. They found that using a lightweight claw resulted in claw vacuum remaining above 32 kPa during milking, and liner stripping was prevented.

Regarding the backflow phenomenon in the liner, Enokidani et al. (2023) examined the relationship between flow rates and the internal diameter of the liner; narrower internal liner diameters were associated with backflow, with the diameter of the junction point (i.e., where the liner bore meets the short milk tube) having the strongest effect on this relationship. Rasmussen et al. (1994) also described the relationship between milker handling and the backflow phenomenon and found that the risk of backflow is highest at the time of liner attachment and removal. Thus, it is clear that inadequate milking equipment and milker handling affect teat end damage and mastitis risk.

Liners are made of rubber and silicone materials consisting of one or two components. These liners can be classified

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into types based on their internal shape, such as round, triangular, square, clover-shaped, or round with ribs on the outside. Liners can be further classified based on the air vent position, i.e., mouthpiece vent, short milk tube vent, or claw vent. There are liners of many combinations of shape and air vent position available in the dairy industry. Unfortunately, it is not clear which of these combinations are optimal for maintaining a healthy teat end condition. Numerous factors need to be considered when evaluating liner performance, such as their impact on teat tissue health and milking performance.

The liner is the only piece of milking equipment that is in direct contact with the teats. The physical pressure attributed to liners (liner overpressure) can cause significant changes in teat tissue (Bade et al., 2009; Fasulkov et al., 2014; Mein et al., 2003; Mein and Reinemann, 2014), which can influence dairy cow performance and mastitis risk. The physical function of the liner is controlled by the pulsation setting and the vacuum setting (Upton et al., 2016). Gleeson et al. (2004) reported that liner design has a greater impact on teat tissue changes and dairy cow performance than pulsator setting. They reported that liner shape and other factors are also important for maintaining healthy teat tissue.

It is understood that the effect of the liner on teat tissue depends on the vacuum setting, pulsation rate and ratio setting, and the performance of the liner itself. Gleeson et al. (2004) reported that liner design plays a greater role in teat tissue changes and milking performance than pulsation settings. Regarding the differences in milking conditions with and without pulsators, Butler et al. (1992) and Capuco et al. (1994) reported a 36% decrease in milk yield and a sevenfold increase in somatic cell count without pulsation, respectively. Regarding pulsation rate and pulsation ratio, Rosen et al. (1983), Thomas et al. (1991, 1993), and Spencer et al. (2007) reported that average and peak milk yields increased and milking time decreased as the pulsation ratio and operating vacuum increased.

The effect of liners on teat tissue was also described in terms of the change in the shape of the teat tissue and teat end edema after milking. Fasulkov et al. (2014) and Gleeson et al. (2004) used ultrasound imaging to measure the changes in the shape of teat tissue after milking. They reported that the recovery of changes in teat tissue properties due to milking, such as teat wall thickness and teat canal length, takes time and that these factors require caution when increasing daily milking frequency.

The aim of this study is to survey of liners in Japan was conducted to determine the liner characteristic currently in use.

MATERIALS AND METHODS

TEAT END LOCATION SURVEY DURING MILKING

Teat end location in a liner under vacuum, i.e., the position of the terminal tip of the teat end that is sucked into the liner during milking, was assessed using a clear plastic liner shell and silicone liner in a double 8 parallel parlor. A total of 33 front and rear teats were surveyed to determine the depth of the teat end in a liner during milking. The depth of seven teats was surveyed simultaneously at the beginning, middle, and end of the milking session. The width of the lip of the silicone liner mouthpiece was 3 cm; this value was excluded from all measurements.

INVESTIGATION OF LINER CHARACTERISTICS

Measurement of Liner Hardness (Without Shell)

A device for measuring the hardness of the liner was prepared (fig. 1). The test liner was connected to a small vacuum pump equipped with a vacuum gauge (ULVAC, Inc., Kanagawa, Japan), a commercially available liner plug (Dairyman Co. Ltd., Hokkaido, Japan) was attached to the liner mouthpiece, and vacuum was applied in five steps (0 kPa, 5 kPa, 10 kPa, 15 kPa, and 20 kPa) to measure the bore thickness (unit: cm) of the middle portion of the liner bore (the point at which the liner bore thickness would be smallest). The percentage change in liner bore thickness for the four other vacuum levels was compared to the liner bore thickness at 0 kPa. The correlation between the percentage change in the liner bore thickness and those at the touch-point, the vacuum level at which the opposite sides of the internal liner surface begin to touch (as defined by Graeme et al., 2009), and the closure-point, the vacuum level at which the liner bore completely closes, were also investigated.

Measurement of Liner Hardness (With Shell)

A liner attached to a shell was set in the experimental testing device (fig. 1C), a transparent acrylic plate was placed over the liner mouthpiece, and the changes inside the liner were captured using a video camera. A right-angled pipe was used at the connection between the liner and the vacuum pump, and a smartphone was placed below the right-angled pipe as a light source. The vacuum at the touch-point was investigated using the video captured by the video camera. The closure-point was taken as the vacuum level when no light was visible from inside the liner, indicating complete closure. The maximum vacuum level was set at 50 kPa, which is the setting used for a normal highline operating system.

MOLDING OF LINER INTERNAL BORE WITH SHELL

In order to clarify the internal shape of the liner at the time of the pulsation opening phase, the following procedure was used to make a mold of the inside of the liner:

Molding Procedure

1. The liner shell was divided vertically into two parts.
2. The two parts of the shell were reset and the liner was set.
3. A mold release agent (KBM-9418-40, Shin-Etsu Chemical Co., Ltd., Japan) was applied to the inside of the liner set in the shell.
4. A rod was inserted inside the liner, and silicone mold agent (base material: KE-1414, hardener: CX-32-1714, Shin-Etsu Chemical Co., Japan) was applied to the inside of the liner.
5. After waiting for the mold agent to cure, the mold was removed using a rod.
6. If the mold could not be removed successfully, the liner was cut and the mold was removed.

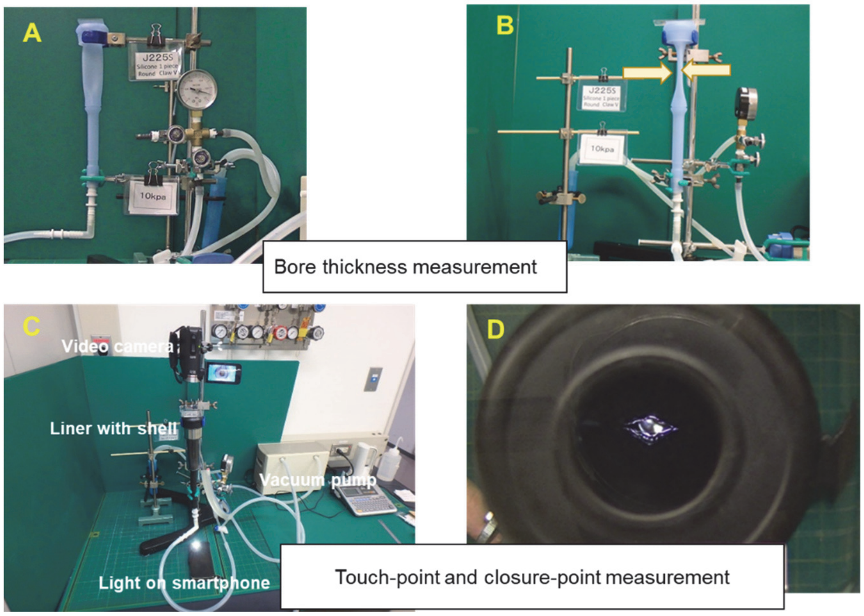

Figure 1. Methods used to measure touch-point, closure-point, and bore thickness. (A) and (B) Measurement of the liner bore thickness, Arrows: measurement point in (B); (C) Experimental testing device; (D) measurement of touch-point and closure-point.

Moldig of Internal Liner Shape Under 40 kPa Vacuum With Shell

To mold the inside of the liner during the pulsation closing phase, a procedure based on that used to mold the inside of the liner under 40 kPa vacuum was used (the vacuum level was taken as the claw vacuum level during milking). A 40 kPa milk claw vacuum level was applied to close the liner, and plaster was poured inside the pulsation chamber to keep the liner in the closed shape, i.e., in the same shape as that during the milking phase. The plaster was then allowed to harden at room temperature for 1 day, after which silicone molding agent was injected. When the dried silicone had cured after standing at room temperature for 1 day, the shell and the external plaster were removed, and the mold of the internal liner shape was removed and cut into 1 cm sections from the liner mouthpiece. This process was used to produce a cross-sectional area of the internal shape of the liner. For various liners, we compared how the cross-sectional area of the liner changed along the length of the liner. The cross-sectional areas at depths of 4 cm to 11 cm from the liner mouthpiece were calculated and compared using the lena-raf220b plugin (Atelier M&M, Tokyo, Japan) for Microsoft Excel (Microsoft, Redmond, CA).

Pulsation-Induced Volume Change Inside the Liner

The change in the internal liner volume during the opening and closing of the liner by pulsation was measured using the following procedure:

Procedure for Measuring the Volume of the Liner Bore Section Under Non-Vacuum Attached to the Shell

1. The junction point (i.e., the junction between the liner bore and the short milk tube) was filled with a stopper to prevent water from passing through the short milk tube.
2. Water was poured through the liner inlet to fill the mouthpiece chamber and the liner bore.
3. The liner plug was used to plug the liner mouthpiece and let the water overflow.
4. The water in the mouthpiece chamber and liner bore sections was drained into a plastic container, and the weight (*A*) of the water in the container was measured in grams (g). Since the density of water is 1.0 g/cm^3, g could be converted to *A* cm^3.

Volume Measurement Under Vacuum (Measured Value B cm^3)

1. The pulsation chamber was filled with water before applying a vacuum following the plugging of the liner mouthpiece. The water level in the pulsation chamber was lowered as the liner bore was compressed during the closing phase, and the internal vacuum of the liner was increased to 40 kPa from the short milk tube side (i.e., from the milk claw) by a vacuum pump. The water level in the pulsation chamber decreased as the vacuum in the liner bore closing.
2. Water was taken from the container with a pipette and injected through the short pulse tube connecting pipe until the pulsation chamber was full of water.
3. The weight of the plastic container (*B*) was measured in grams (g) and recorded. Since the density of water is 1.0 g/cm^3, the weight of *B* was taken as the volume of the bore section (cm^3) during the 40 kPa vacuum milking phase.
4. The change in the volume of the pulsation chamber, i.e., *A*-*B* (cm^3), and the pulsation chamber volume shrinkage ratio B/A (%) were calculated.
5. The above operations were performed in triplicate, and no significant differences were observed in the measured volumes.

Statistical Analysis

Following the Kruskal-Wallis test, post hoc tests were performed using the Stat View statistical package to compare the three groups. The coefficient of determination, r^2, was calculated using Excel 2019 (Microsoft Corp.).

Results

Results of Teat End Position During Milking

The depth to which the end of the teat penetrated the liner during milking is shown in figure 2. The depth of the teat-end position is shown, excluding the 3.0 cm mouthpiece lip of the liner. The depth of the teat-end position for 33 teats was between 4.0 cm and 7.5 cm for the front teats and between 3.5 cm and 6.0 cm for the rear teats. The mean ± standard error was 5.3 ± 0.7 cm for the front teats and 4.4 ± 0.7 cm for the rear teats, with penetration of the front teats into the liner being significantly deeper ($P<0.01$). In addition, the change in depth during a single milking session (mean ± standard error, 7 teats) was 3.9 ± 0.8 cm for the early stage of milking, 4.6 ± 0.7 cm for the middle stage of milking, and 4.9 ± 0.5 cm for the late stage of milking, indicating that teats were sucked deeper into the liner ($P<0.01$) as the milking stage progressed.

Measurement of Liner Internal Characteristics

Investigation of Liner Hardness

Figure 3 shows the results of the hardness measurements of 24 test liners without shells. When a vacuum of 10 kPa was applied, the liner bore thickness ranged from 35% to 95% of that at 0 kPa among the liners, showing a large difference. Hard liners showed only a small change in the liner bore thickness, while soft liners closed almost completely.

When the liner was attached to the shell, the touch-point was distributed between 10 kPa and 17 kPa, as shown in table 1. The closure-point of round liners was distributed between 14 kPa and 36 kPa; however, the triangular, square, and clover-shaped liners did not completely block light even when a vacuum of 50 kPa was applied, and there was no complete adhesion of the internal surface. A positive correlation was observed between the percentage change in liner bore thickness and the touch-point, but only at pressures of 10 kPa vacuum ($y = 7.678x + 9.6249$, $R^2 = 0.6742$). No correlations were observed among the other vacuum conditions and the touch-point.

Molding of Liner Shape

External and Internal Liner Shapes

The external (fig. 4, left column) and internal (fig. 4, center column) shapes of the liners under non-vacuum conditions are shown in figure 4. Liners were named based on their internal shape. The junction point shape (fig. 4, right column), i.e., the area where the liner bore meets the short milk tube, was also variously shaped, with the hourglass-shaped junction points being the most common, and wine glass-, cocktail glass-, and tumbler-shaped junction points also observed. Only the round liner with ribs on the outside had a junction point area that was markedly different in shape.

Internal Shape of Liners Under a Vacuum of 40 kPa

Figure 5 shows the sequential cross-sections of the liner interiors obtained by cutting the mold of the liner bore interior prepared under a vacuum of 40 kPa at 1-cm intervals from the liner mouthpiece. This vacuum level was used to simulate the claw vacuum during milking.

In the round liner, the liner bore area size (unit: cm^3) changed at a liner depth of 4 cm to 10 cm. The bore area size was the smallest at a liner depth of 5 cm, where the bore thickness was approximately 0.5 cm; however, notably, the bore in the round liner was observed to constrict in the center, with open spaces on either side of the central point, forming a figure 5 in cross-section. The elliptical liner resembled the shape of round liners. In the triangular liner bore, one side was collapsed and the bore area size changed slightly at a liner depth of 6 cm to 9 cm; however, the triangular cross-section remained large and the bore did not close completely. In the square liner bore, the bore closed in a diamond shape, with the largest change in bore area size occurring from a depth of 5 cm to 9 cm. Compared to the triangular and clover-shaped liner bores, the bore area size of the square liner remained smaller in the center than at both ends. At a liner depth of 6 cm to 7 cm, the bore thickness was the smallest at about 0.5 cm. In the clover-shaped liner, the bore area size

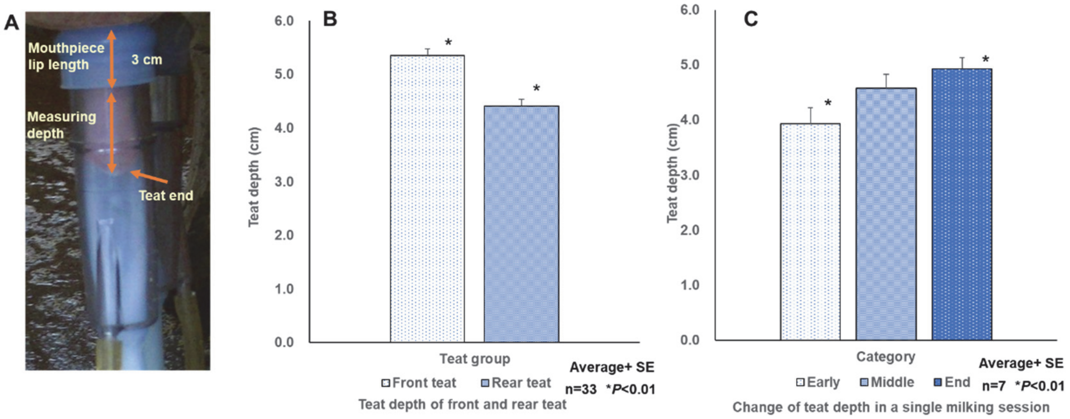

Figure 2. Change in the teat depth in the liner during a single milking session. (A) Photograph of teat-end position during milking and the depth of the teat that is measured; (B) Depth of front and rear teats during a single milking session (excluding mouthpiece lip length) at a double-8 parallel parlor; (C) Change in teat depth during a single milking session. Early, middle, and end refer to the time after the start of milking at a double-8 parallel parlor.

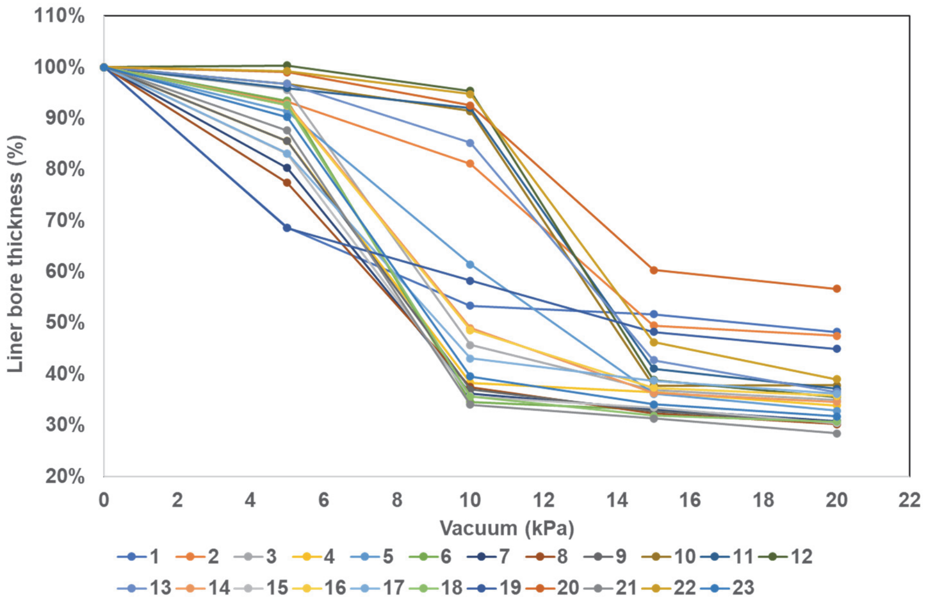

Figure 3. Liner bore thickness of the middle section with no shell under different vacuum levels relative to the bore thickness at 0 kPa. Numbers in the legend indicate different test liners.

Table 1. Comparison of touch-point and closure-point of liners with different characteristics.

Liner Number	Manufacturer	Liner Shape	Vent Location	Material	Touch-point[a] (kPa)	Closure-point[b] (kPa)
1	A	Round	Claw vent	Rubber	14	36
2	A	Round	Claw vent	Rubber	11	24
3	A	Round	Claw vent	Rubber	14	24
4	B	Round	Claw vent	Rubber	17	28
5	B	Round	Claw vent	Rubber	17	20
6	B	Round	Claw vent	Rubber	17	19
7	B	Round	Claw vent	Rubber	17	20
8	C	Round	SMT vent[c]	Rubber	17	20
9	D	Round	Claw vent	Rubber	13	20
10	E	Round	Claw vent	Rubber	12	24
11	F	Round	Claw vent	Rubber	13	20
12	K	Round	Claw vent	Rubber	15	25
13	K	Round	Claw vent	Rubber	10	14
14	L	Round	Claw vent	Rubber	17	20
15	A	Round	Claw vent	Silicone	14	24
16	A	Round	Claw vent	Silicone	14	26
17	A	Round	Claw vent	Silicone	12	21
18	A	Round	Claw vent	Silicone	14	24
19	C	Round with rib	SMT vent[c]	Rubber	12	19
20	H	Round with rib	MP vent[d]	Silicone	14	17
21	D	Clover	Claw vent	Rubber	15	50[e]
22	G	Elliptical	Claw vent	Rubber	11	30
23	I	Square	Claw vent	Rubber	13	50[e]
24	J	Triangular	MP vent[d]	Rubber	14	50[e]

[a] Touch-point was investigated using a video camera.

[b] The closure-point was taken as the vacuum level when no light was visible from inside the liner.

[c] SMT: Short milk tube vent.

[d] MP: Mouthpiece vent.

[e] Closure-point vacuum could not measure at 50 kPa.

was smallest at liner depths of 4 cm to 7 cm, but the cross-section remained clover-shaped and did not close completely. Liners with side ribs on the outside of the bore (fig. 5, row C) had a like round bore shape, with the bore area size remaining larger than that observed in normal round liners. The bore section collapsed at a liner depth of 5 cm to 8 cm, with a minimum bore thickness of about 0.5 cm observed at a liner depth of 5 cm. Liners with vertical ribs on the outside of the bore (fig. 5, row B) retained a larger bore area size than normal round liners. The depth of the bore section in these liners ranged from 6 cm to 9 cm, with the bore thickness reaching approximately 1.0 cm at a liner depth of 7 cm. Liner bore area sizes between the vertical and side ribbed liners differed in the position where the liner bore collapsed the most.

Figure 4. Outer (left), inner (middle), and junction shape (right) of liner when no vacuum was applied. These pictures show each liner outer and inner shape with no vacuum.

MEASUREMENT OF CROSS-SECTIONAL AREA OF LINER UNDER VACUUM

Figure 6 shows the cross-sectional area (cm^2) of the rubber and silicon mold inside the liner when it was cut at successive 1-cm lengths extending from the mouthpiece of the liner. The cross-sectional area of each liner bore was smallest at liner depths of 6 cm to 8 cm from the mouthpiece. The cross-sectional areas of the triangular liners, clover-shaped liners, and round liners with ribs were larger than those of round and square liners.

This figure is a cross-sectional view of the inner shape of liners at 1-cm intervals under 40 kPa. The red insets show the range in the teat-end position in the liner at the time of milking.

VOLUME CHANGE INSIDE THE LINER

Table 2 shows the volume change inside the liner during the closing and opening phases (under 40 kPa). The normal volume of the liner under the opening phase (non-vacuum, *A,* cm^3) varied widely from 41.6 cm^3 to 80.4 cm^3. The inner liner volume (*B*, cm^3) under a vacuum of 40 kPa varied markedly among liners, although most values for *B* were approximately 30 cm^3. The shrinkage volume (*A–B* in table 2) of liners other than round liners was relatively small (<30 cm^3). The elliptical liner was flat shape, so the volume change was small. On the other hand, some round liners had a shrinkage ratio (B/A in table 2) of 60% or more due to the relatively large extent to which the bore collapses. However, even with round liners, the shrinkage ratio decreased and became less likely to collapse when the liners had outer ribs.

DISCUSSION

Liners can be classified into different types based on the location of the air vent that is used to push the milk slug into the long milk tube during milking: mouthpiece-vented, short milk tube-vented, and claw-vented types. (Gomez et al., 2011). It is not clear which of the three vent locations is better for milking performance and mastitis prevention. Spencer and Rogers (1991) and other authors have investigated the relationships among liners and liner slipping. They reported that liners that were associated with greater liner slipping were also associated with an increased incidence of new mastitis infections. Gomez et al. (2011) and Leonardi et al.

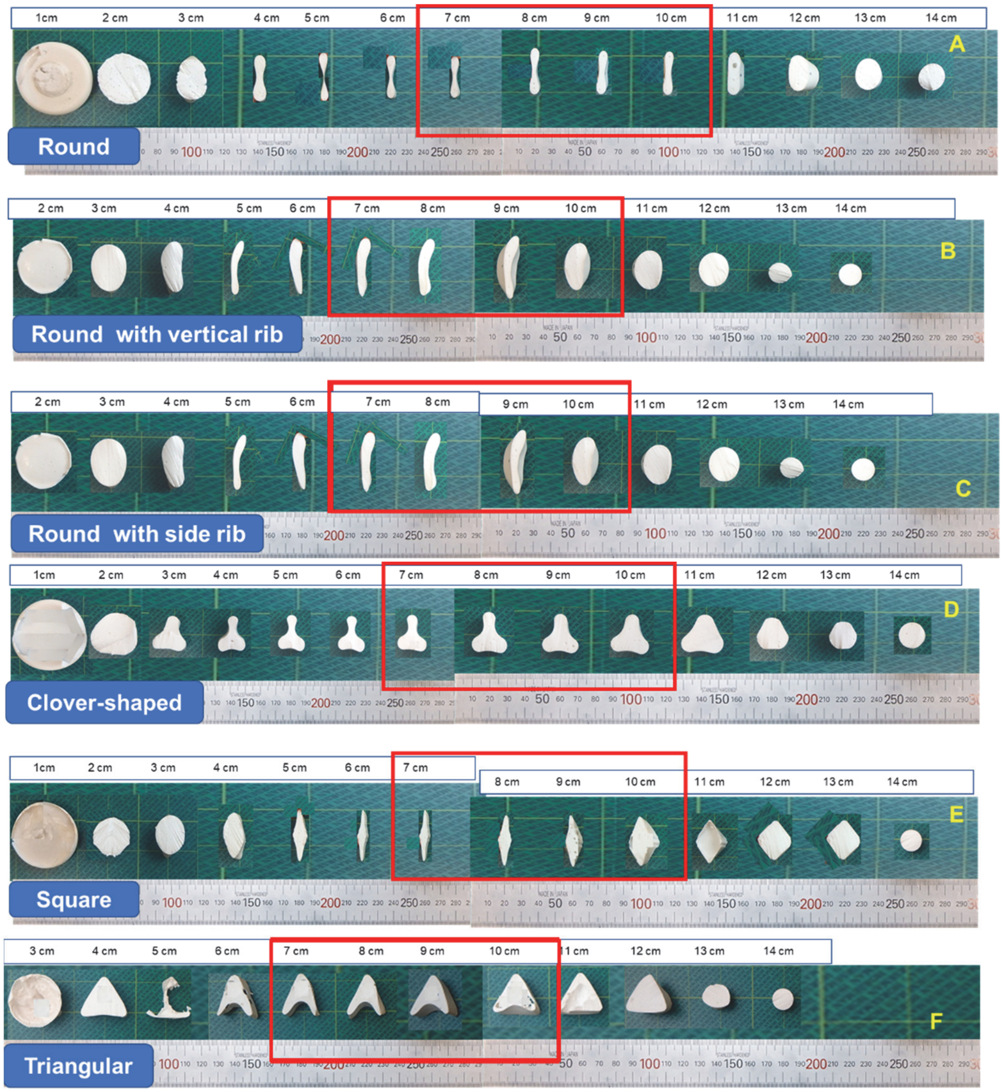

Figure 5. Shape of 1-cm sections of the liner bore interior prepared under a vacuum of 40 kPa. The value above each section (cm) shows the position from the mouthpiece lip. The red square shows the position of teat end during milking.

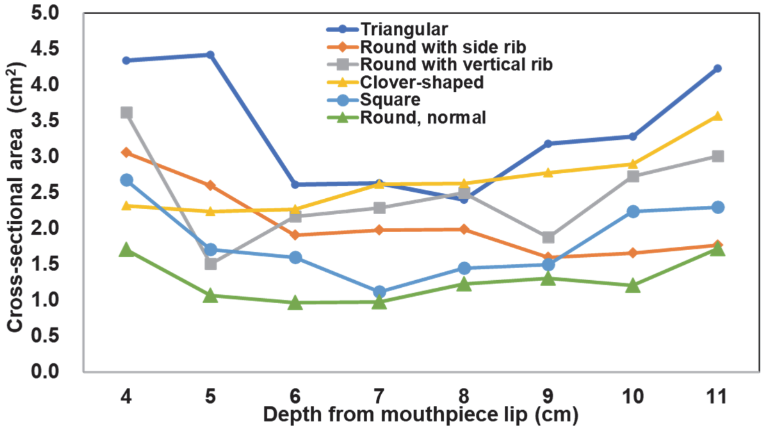

Figure 6. Comparison of liner cross-sectional area at closing phase under 40 kPa on depth from mouthpiece lip.

(2015) examined the influence of liner shape and material. Their findings showed that the extent of liner compression and teat overpressure differed depending on liner material and shape. Thus, despite the importance of liner performance, the most suitable liner types according to liner shape and liner vent location for milking and preventing mastitis remains unknown, and many different liner types are currently commercially available.

The health of teat tissue, especially the condition of the teat end, is closely related to the incidence of mastitis, and

Table 2. Comparison of change in liner volume during the opening and closing phase in liners with different characteristics

Liner Number	Liner Shape	Bore Material	Volume under No Vacuum (A, cm^3)	Volume under 40 kPa Vacuum (B, cm^3)	Volume (A-B, cm^3)	Change Ratio (B/A,%)
1	Round	Rubber	61.9	33.6	28.3	54.3
2	Round	Rubber	49.9	30.5	19.4	61.1
3	Round	Rubber	57.7	33.5	24.2	58.1
4	Round	Rubber	44.5	27.8	16.7	62.5
5	Round	Rubber	45.7	28.8	16.9	63.0
6	Round	Rubber	41.6	26.4	15.2	63.5
7	Round	Rubber	53.1	32.3	20.8	60.8
8	Round	Rubber	66.8	35.2	31.6	52.7
9	Round	Rubber	55.9	32.5	23.4	58.1
10	Round	Rubber	56.2	34.8	21.4	61.9
11	Round	Rubber	51.8	30.2	21.6	58.3
12	Round	Silicone	60.8	34.8	26.0	57.2
13	Round	Silicone	80.4	35.5	44.9	44.2
14	Round	Silicone	78.7	38.0	40.7	48.3
15	Round	Silicone	47.5	26.4	21.1	55.6
16	Round with rib	Rubber	46.7	25.4	21.3	54.4
17	Round with rib	Silicone	60.2	26.0	34.2	43.2
18	Clover-shaped	Rubber	48.8	25.0	23.8	51.2
19	Elliptical	Rubber	46.5	25.3	21.2	54.4
20	Square	Rubber	45.1	23.1	22.0	51.2
21	Triangular	Rubber	76.7	40.3	36.4	52.5

the teat end must be prevented from becoming injured, congested, or hyperkeratotic (Capuco et al., 1994; Gleeson et al., 2004).

In order to determine the effect of the liner on the teats, especially the teat ends, it must be determined where the teat ends reside within the liner during milking. In this study, when the position of the teat end inside the liner was investigated during milking, the teat end was located 7 to 10 cm (including lip length) from the mouthpiece of the liner. Leonardi et al. (2015) reported that a liner depth of 6.5 cm from the liner mouthpiece is well suited for measuring teat end position. The results of this study showed that the front teats were sucked deeper into the liners than the rear teats. The increased depth of the front teats may be due to the parallel milking system. It was also found that the depth of the teats in the liners late in the milking session was deeper than that at other times during a milking session. This may be because teats become slender in the late stage of the milking session as milk yield decreases and the teats are sucked further into the liner. These findings indicate that the conditions in the liner at a depth of 7 to 10 cm have the most marked effect on teat ends.

Regarding the internal diameter of the liner, Enokidani et al. (2023) reported that vents at the mouthpiece appear to be optimal. However, assessing the performance of mouthpiece vents is important regardless of teat shape or teat size. They also reported that the backflow of milk in the liner can be attributed to the change in the volume of the liner. The results of this study showed that the change in the liner volume associated with the opening and closing phases of the pulsation cycle tended to be larger in round liners compared to the liners of other shapes.

Numerous studies have been published on the use of ultrasound devices to monitor specific changes in teat tissue during milking (Gleeson et al., 2004). Mein et al. (2003) reported that the changes that occur in teat tissue due to milking are exacerbated when the liner is closed and the teat is massaged, compared to when the liner is open. Consequently, the degree of teat overpressure during milking by the liner may have a marked effect on teat tissue condition.

The effects of physical pressure (teat massage) on the teat end caused by the liner closing phase have been described in detail in numerous studies (Butler et al., 1992; Davis et al., 2000; Mein et al., 2003; Gleeson et al., 2004; Zucali et al., 2008; Graeme et al., 2009; Penry et al., 2016, 2017a,b). These studies reported that the most important factors affecting teat end massage by the liner are pulsation ratio, pulsation rate, pulsation chamber vacuum, and touch-point in the static phase (when the milking system is idling). In fact, however, during the dynamic phase (during milking), the liner compression (average claw vacuum minus liner collapse vacuum), overpressure, liner compression during the closing phase, liner bore size, and liner age, all change throughout the process. The true closing milking ratio during milking fluctuates as a dynamic value (Graeme et al., 2009). In addition, these studies reported that shorter milking times are better for the teat condition, as this means that cows are not subjected to liner overpressure during long milking sessions and over the long term.

Graeme et al. (2009) defined the touch-point as follows. This method is fast, repeatable, and simple for round liners, but it is not applicable to triangular or square liners where the opposite internal surfaces of the bore do not touch each other. The touch-point method was used for the triangular and square liners in this study to confirm that the internal surfaces of the liner do not touch, even when maximum vacuum is applied. Although different from the round liners, partial contact of the opposing internal surfaces of the triangular and square liners was observed. Difficulties in getting the opposing internal surfaces of the liner bore to touch may result in insufficient pressure for teat overpressure, and it is important to check the internal shape of the liner during the closing phase as well as the depth of the teat end in the liner. If the internal closure (change) is small, then there is insufficient pressure to press the teat, which may cause teat damage. The use of hard liners should be reduced to prevent overpressure from becoming too low, and the total time of teat exposure to overpressure should be reduced by reducing milking time. In particular, Graeme et al. (2009) reported that milk yields are less than 1 kg/min when the claw vacuum is in the 42 to 45 kPa range. Teat pressure within this appropriate range depends primarily on the shape and performance of the liner. Comparing the performance of various liners can be important for maintaining teat tissue health.

Liner collapse was compared with and without shell attachment. With shells, a conventional touch-point method was used for comparison. The results showed that the different liners had varying degrees of hardness. Liner bore hardness measurements showed no significant difference under a vacuum of 5 kPa, but large differences appeared depending on the liner under a vacuum of 10 kPa, and a positive correlation between the percentage change in the liner bore thickness and the touch-point was observed. The hardness of the liner could be easily measured under a vacuum of 10 kPa. When replacing or renewing the liner, it is important to consider the effect of the liner on the teat and to select a liner of similar hardness to the previous liner used.

The results of this study on the cross-sectional area and internal shape of the liner bore when the liner closes or opens suggested that round liners have a small cross-sectional area where the teat end is located, and that the bores area are large enough to press the teat end sufficiently. On the other hand, it is also assumed that the pressure is generally too high at the closing phase. The cross-sectional area of liners other than round ones varied among liners in our study results. The clover-shaped and triangular liners have a larger cross-sectional area, and it is assumed that the teat massage pressure associated with these liners may be insufficient in the part of the liner where the teat ends are located.

In this study, touch-point was measured for non-round liners to confirm whether the liners closed during the closing phase. Furthermore, by molding the inside of the liner during the closing phase, the cross-sectional area of the liner during the closing phase at the teat-end depth could be determined. The results showed that round liners could close down to a size of about 0.5 cm, indicating that sufficient teat pressure was achieved. At the same time, by measuring the liner closing pressure (i.e., the closure-point), which is indicative of overpressure, it became clear that some liners were harder and others softer. For liners other than round ones, the cross-sectional area of the teat-end position was large under a vacuum of 40 kPa, which is typically set as the claw vacuum level at milking (not operating vacuum). This vacuum level may have been too large to generate sufficient teat overpressure.

The effect of the degree of liner overpressure on the teat tissue of dairy cows has a significant impact on milking speed and teat tissue condition, both of which affect milk yield and quality (Graeme, 2012). All of the force created by the milking equipment is transmitted to the teats by the liner, and the shape of the liner affects the teat tissue more significantly than the pulsation setting. Therefore, liner performance is important, and the analysis of liner performance is of great significance to dairy farmers.

When comparing liner touch-point, which is widely used as an indicator of liner performance, there was a significant difference among liners of different hardnesses (i.e., there were hard and soft liners); liners with narrower junction point diameters tended to be harder. Teat ends were positioned at depths of 7 to 10 cm in liners during milking, with penetration into the liner being greater for the front teats, especially at the end of milking. This sucking position was where teat pressure was applied.

When molds of the inside of the liner were produced during the closing phase, the cross-sectional area at the teat end position was large for all shapes of non-round liners, raising the question of whether the teat overpressure obtained with these liners was sufficient.

The shape of the liner bore and the size of the mouthpiece lip section had a greater effect on liner volume change than the liner material. Clover-shaped, triangular, and square liners all close with angles and have relatively small closure volumes. It is considered that not only the closure of the bore section, but also the size (inner diameter and length) of the bore section itself has an effect on liner volume change.

CONCLUSION

A wide range of differences in the hardness of commercially available liners was observed. The cross-section area of the internal bore of liners during the closing phase was smaller for round liners and larger for non-round liners.

Non-round liners were assumed to reduce overpressure on the teats during milking and to reduce the volume change during the opening and closing phase; however, the actual degree of overpressure that is applied to the teat end is unknown. The effect of the liner on teats is completely separate from other milking factors and needs to be studied in depth from the two perspectives of both milking performance and mastitis prevention.

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