Pressure distribution at the teat–liner and teat–calf interfaces

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ABSTRACT

During milking, the teat is loaded because of a combination of vacuum and pressure of the collapsing liner. It is assumed that pressure concentrations tend to cause teat-end injuries and hyperkeratosis. The pressure distribution on the bovine teat was measured to test the hypothesis that the pressures of the collapsed liner are unevenly distributed over the teat. With the aid of a pressure-sensitive sensor (approximately 2 gauge points/cm²), the pressures at the teat–liner and the teat–calf interfaces were measured at 100 Hz. Pressure distribution over the surface of an artificial teat was measured with 7 different liners, 1 liner at 3 different vacuum levels, and a suckling calf. One cow was equipped with a sensor at a teat during a milking with one of the liners. Conventional round liners concentrated the load over 2 sites at the teat end. Some liners (softer material, reduced tension, smaller barrel, reduced mouthpiece depth) distributed the compressive load over a larger area of the teat. Although all liners distributed the highest pressures at the teat end, some liner designs showed a 25% reduction at the site of interest at vacuum of 44 kPa. The calf forced milk flow by a combination of suckling and overpressure in the teat cistern caused by the tongue. While the calf was swallowing, teat pressure was reduced because of a decrease in vacuum. Moreover, the calf did not load the teat end, probably because the teat canal would be closed and the milk would not flow. The method of using a pressure sensor to analyze teat loading at the teat–liner and the teat–calf interfaces showed potential and is a first step toward developing a natural milking technique.

Key words: machine milking, teat loading, liner design, teat health

INTRODUCTION

The teat canal is a strong and important primary barrier against invasion of mastitis pathogens into the

udder (Hamann, 1987). The sphincter muscle surrounding the teat duct is tightly closed between milkings and impedes bacterial intrusion from the teat opening into the interior of the gland (Nickerson, 1994). Good condition of the teat end, teat canal, and sphincter muscle is needed to minimize the risk of mastitis (Michel et al., 1974; Hamann, 1987; Neijenhuis et al., 2000). The combination of vacuum and compression of the liner during milking can be a source of serious repetitive stress to the teat.

During milking, teat length and tissue thickness change because of mechanical forces exerted by the vacuum and the collapsing liner (Hamann and Stanitzke, 1990; Neijenhuis et al., 2001). The mechanical stresses result from interaction between vacuum, liner properties, liner on-time, and teat anatomy (Hamann, 1987). As the liner closes around the teat end, the teat canal closes first just below the middle region of the canal. Presumably, this region is adjacent to the most incompressible part of the teat end where the liner encounters greatest resistance to bending. Hence, the highest pressure is exerted at this site (Mein et al., 2003).

Under normal conditions, teat tissue will adapt to these repetitive loadings. However, teat-end tissue sometimes suffers from hyperkeratosis (Neijenhuis et al., 2000). Hyperkeratosis was markedly reduced when the average milking time per cow was decreased by using automatic cluster removers or when pulsation was disabled and milking was performed without compression of teats (Tolle and Hamann, 1978; Rasmussen, 1993). On the other hand, hyperkeratosis was increased because of pressure using compressed air during the D phase of pulsation (Hamann et al., 1994). Teat loading during the D phase of pulsation should be high enough to relieve congestion and edema in teat tissues, but too much loading may lead to hyperkeratosis (Bade et al., 2007).

Calf suckling caused less teat tissue swelling and less (severe) teat hyperkeratosis than milking (Hamann and Stanitzke, 1990; Neijenhuis et al., 2000, 2001). Moreover, based on a 6-mo observation period, calf suckling caused significantly fewer new mastitis infections than milking (O'Shea and Meaney, 1979). Unlike the situa-

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tion in machine milking, a calf isolates the teat cistern from the mammary gland by applying compressive pressure near the base of the teat. Milk flow is forced by a combination of suckling and overpressure in the teat cistern caused by the tongue. While the calf is swallowing, teat pressure is decreased because of a decrease in vacuum (Fischer, 2007).

There is no consensus as to what constitutes an adequate liner compared with an inferior liner, and liner design has remained an empirical art. A method for measuring teat loads would have potential for quantifying liner characteristics and for developing tailor-made liners for different breeds or individual herds. Such measurements could be used to assess current liner designs, determine the effects of changing various liner properties, and study the effects of liner aging. Knowledge of teat pressures is necessary to establish boundary conditions in analytical models to predict tissue stresses (Gates and Scott, 1986).

The aim was to develop a technique for pressure measurement at the teat liner and teat-calf interface. Many attempts have been made to measure the compressive pressure at the teat using methods varying from ultrasound techniques to the use of pressure transducers (Davis et al., 2001). The use of a new pressure sensor produced a high spatial-temporal resolution of real-time pressures; hence, the dynamics of the pressure distribution at the teat during a single pulsation cycle can be measured. The main objective was to measure teat pressures during calf suckling and machine milking with different types of liners and different vacuum levels. The effects of liner properties and milking machine settings were evaluated.

MATERIALS AND METHODS

The measurement device consisted of a flexible pressure-sensitive layer. The pressure-sensitive layer was attached to a flexible resin film through which electrodes faced each other, and included high conductivity flaky carbon particles and low conductivity amorphous-based carbon particles. When pressure was applied to the resin films, the average distance between the carbon particles was decreased, causing a tunnel conduction phenomenon and resulting in a decrease in electrical resistance between the electrodes. The assembly resulted in a very thin pressure-sensitive sensor (0.75 mm) and contained 10 elements (gauge points) in the longitudinal axis and 1 element in the transverse axis; all elements had a pressure-sensitive area of 7.5×6.0 mm. There was a linear relationship between the applied liner load and conductance between the electrodes. The sensor measured with a spatial resolution of about 2 gauge points/cm² and a frequency of 100 Hz. The sensor was small

enough to bend along the teat circumference and flexible enough to bend in longitudinal direction as well. A pilot study showed that the sensor recorded barely any pressure when bending it and when no normal force was applied. During measurements, the offset was determined (open liner) and automatically subtracted by means of the software. The sensor was calibrated with a sphygmomanometer, whereby the air bladder cuff and the sensor were placed between 2 fixed parallel plates while the bladder was inflated in increments of 10 mmHg in a range of 10 to 300 mmHg. Calibration was done before and after the measurements.

The manufacturer of the sensor claimed that the sensor was not sensitive to shear forces, and we tested this claim. A slider was fixed between 2 parallel plates of steel. The sensor was fixed with 2-sided adhesive tape to the bottom plate, and 3 mm of rubber was glued on the slider at the side where the sensor was placed to apply shear force to the sensor. On the other side of the slider, some grease was applied to allow sliding (steel on steel). The assembly could be squeezed in between the 2 plates, and it was possible to slide it slowly with the electrical screw driver. When silicone spray was used between the sensor and the rubber sheet, the sensor readings showed local pressure increases and decreases of about 2.5%. Generally, the (normal) pressure remained constant. Because the smooth surface and possible coating with silicone spray should have minimized any potential development of shear forces inside the sensor, and because the test of a horizontal pull did not reveal any significant sensitivity to shear forces, we do not think shear forces would have degraded the sensor's pressure readings. Nevertheless, without more extensive testing we could not exclude the possibility that shear forces across the sensor may have played a role ($\pm 2.5\%$) in the pressure readings obtained, affecting the absolute values of those readings.

Because of the small size of the sensor and to capture the pressure distribution at the complete circumference of the liner, the sensor and (artificial) teat combination was rotated 12 times in increments of 30° relative to the liner or calf. The pressure distribution was then measured for about 20 s. After each session, the artificial teat was turned through an angle of 30° with respect to the liner or calf and the next session was recorded. An objective comparison between the pressure distributions could only be made when the teat tissue remained unchanged during the measurements. Because tissue properties of a real cow teat change during milking, over a lactation, and between lactations, the liners and the calf were tested by the use of an artificial teat. To transfer the results of pressure distributions of the artificial teat to daily practice, one of the liners was tested on a live teat equipped with the sensor. The

Table 1. Liner characteristics

Liner number	Liner ¹	Material	Mouthpiece diameter (mm)	Barrel longitudinal shape	Barrel cross-section shape	Barrel diameter at 75 mm (mm)	Wall thickness at 75 mm (mm)	Stretch (%)	Touchpoint ² (kPa)
1	Lely Silicone	Silicone	21	Parallel	Round	24	2.5	4	10
2	Lely Silicone 2	Silicone	21	Tapered	Round	23.5	2.3	0.8	10
3	Happel Aktivpulse	Rubber	22	Special	Oval	24	2.5	3.5	—
4	Lely Rubber	Rubber	21	Tapered	Round	21	2	22.4	10
5	ProSquare	Rubber	20	Parallel	Square	18.25/22.0	2.6	23.5	—
6	Ultraliner Triangular TLC A6	Rubber	20	Parallel	Triangular	26	2.1	15.6	—
7	Silclear	Silicone	21	Parallel	Round-square	19.8	4	7.2	6

¹Lely Silicone, Lely Silicone 2, and Lely Rubber (liners 1, 2, and 4) manufactured by Lely Industries N.V., Maassluis, the Netherlands; Happel Aktivpulse (liner 3) manufactured by System Happel GmbH, Salenwang, Germany; ProSquare (liner 5) manufactured by Ingenieursbureau Heemskerk b.v., Diessen, the Netherlands; Ultraliner Triangular TLC A6 (liner 6) manufactured by Avon Dairy Solutions, Melksham-Wiltshire, UK; Silclear (liner 7) manufactured by Silclear Ltd., Hampshire, UK.

²Touchpoint (kPa) = the amount of pressure needed to close/open the liner.

Figure 1. Different graph types of the pressure in time relative to the maximum pressure at the teat end. Type A = pressure built up and decreased rapidly; type B = pressure increased slowly and decreased quickly; and type C = pressure built up rapidly, immediately followed by a slow decrease. The tangents of the curves were determined between zero pressure and the moment when pressure exceeded 90% of its maximum. The threshold above 90% was chosen to determine the time when a high pressure was exerted to the teat. The graph types describe liner types in Table 2.

soft silicone artificial teat had a length of 77 mm and a rounded distal end. The teat barrel was slightly conical with a diameter of 22 mm at the teat end, 25 mm at the teat base, and a wall thickness of 2 mm along the full length. The artificial teat was wider than some of the small liners used. To mount the liner correctly, it was first stretched by applying some vacuum on the outside to open it and then silicone spray was used to insert it more easily. A milking machine (Lely Astronaut A3, Lely Industries N.V., Maassluis, the Netherlands) was used at a milking vacuum of 44 kPa, a pulsation rate of 60 cycles/min, and a pulsator ratio of 65:35.

Pressure distribution on the artificial teat was measured for 7 different liners, for 1 liner at 3 different vacuum levels (35, 44, and 55 kPa), and with a suckling calf. One cow was equipped with a sensor at a teat during 1 milking with 1 liner. During the pressure measurements on the liner-artificial teat interface, no liquid stream was used because this could affect the teat load. The calf was provided with milk via a tube within the artificial teat to provoke a regular and representative suckling behavior. The liners included Lely Silicone (liner 1; Lely Industries N.V., Maassluis, the Netherlands), Lely Silicone 2 (liner 2; Lely Industries N.V.), Happel Aktivpulse (liner 3; System Happel GmbH, Salenwang, Germany), Lely Rubber (liner 4; Lely Industries N.V.), ProSquare (liner 5; Ingenieursbureau Heemskerk b.v., Diessen, the Netherlands), Ultraliner Triangular TLC A6 (liner 6; Avon Dairy Solutions, Melksham-Wiltshire, UK), and Silclear (liner 7; Silclear Ltd., Hampshire, UK). The characteristics of the 7 liners are given in Table 1.

The liners were compared in relation to the time course of their pressures at the gauge point at which maximum pressure was observed. The variables used for comparison were the gauge point at which maximum

Figure 2. Projections of teat load as measured separately with the pressure sensor and later reconstructed in one image according to this matrix.

pressure was observed (row); maximum pressure (kPa); number of maximum pressure spots; and duration of maximum pressure (s). The duration represented the time over which the pressure was higher than 90% of its maximum pressure observed during the milking (Figure 1). The slopes of the pressure curve during liner collapsing (C-phase) and opening (A-phase) were determined by printing the image on paper and manually determining the angle of the tangents in a semiquantitative manner. The steeper the pressure curve, the faster the increase and decrease, respectively, of the teat load. This feature was related to the time available for the accumulated liquids in the teat tissue to be moved or dispersed. Insufficient time for this could lead to high pressures within these teat tissues.

A Bluetooth dongle (RsScan, Olen, Belgium) sent data to a laptop, and custom-made software processed these data to a pressure distribution. Pressure images were translated to Excel files (Microsoft Corp., Redmond, WA), reproduced with help from a grayscale,

Figure 3. Pressure in time (s) measured at gauge point A7 (Figure 4); the 6 moments during the act of suckling and swallowing are indicated with dotted lines. During moments 1 and 5, no pressure was applied to the teat. From moment 1, the pressure increased to a maximum at moment 3. Thereafter, pressure decreased.

Figure 4. Example of the pressure distribution at the calf-teat interface at moment 3. The columns and rows correspond with the projections described in Figure 2.

and processed in a semiquantitative data analysis. The results were reproduced by means of a flat projection of the teat load in which a linear nearest-neighbor interpolation was used. Between each pair of gauge points an additional interpolated pressure was shown for plotting purposes, but the analysis was only performed on real gauge point data shown in the top-right square of the grid location (Figure 2). The bottom rows of the pressure pattern refer to the teat end, the top rows refer to the base of the teat. By use of the calibration results, the pressures were translated into absolute pressures.

RESULTS

Calf Measurement on an Artificial Teat

Calf measurements over time were divided into 6 moments (Figure 3), with moments 1 to 5 representing suckling phases and moment 6 representing swallowing. Considering the pressure distribution of the calf on the surface of the artificial teat at the moment of maximum pressure, columns A, B, and C in Figure 4 represent the teat load caused by the calf’s palate. The teat load in the other columns is caused by the calf’s tongue. Little or no pressure is exerted at columns D and L because of the transition from tongue to palate. Rows 9 and 10 show the teat-end pressures.

In Figure 3 the pressure at gauge 7A (Figure 4) is shown during calf drinking. During moments 1 and 5, no pressure was applied to the teat. From moment 1, the pressures increased to a maximum at moment 3, and thereafter pressures decreased. The spatial pressure distribution at moments 2 and 4 were comparable to that at moment 3, except that the absolute pressures were lower. The high teat loads at gauge points B2 and B3 (up to 236 kPa during phase 3) were caused by the thickening in front of the calf’s hard palate to constrict

Figure 5. Example of the pressure distribution at the artificial teat-liner interface of a round silicone liner at the moment of maximum compressive load. The columns and rows correspond to the projections described in Figure 2.

the teat at the teat base to prevent the milk from flowing back from the teat cistern into the mammary gland when overpressure in the teat cistern existed. This overpressure was induced by the calf's tongue pressing the entire teat barrel (gauge sites E2 to K8; Figure 4) against the palate. The pressures at these locations in combination with the suckling of the calf caused the sphincter muscle to open and milk to flow. Note that the calf barely loaded the teat end (rows 9 and 10). If it did, it would cause the teat canal to close and milk would not flow. The drinking frequency of the calf was about 2.5 Hz (Figure 3).

Conventional Round Liner Measurement on an Artificial Teat

Pressures measured at row 1 of the pressure distribution of a conventional collapsed liner (Figure 5) were caused by the liner mouthpiece lip. These pressures were

almost equal around the teat. Under the lip (rows 2 to 4), no pressure was measured because the mouthpiece did not touch the teat. From row 5 (just above the mid-point of the teat), the pressure increased progressively until a maximum pressure of 130 kPa at 2 points on the teat apex (C9 and I9). At these 2 sites (180° separated from each other), the liner touched the teat end. Between those 2 points, the pressure decreased to almost zero because the liner did not touch the teat as the liner bends at the edges of its plane of collapse. This does not eliminate the possible shearing stress in the teat tissue. Closer to the sphincter muscle (row 10) no pressure was observed because the liner did not touch the teat because of the stiffness of the liner.

Considering the gauging point of maximum pressure (C9), the pressure course (Figure 6) was roughly the reverse of the pulsation vacuum. While the pulsation vacuum was at maximum (milk phase), the liner was opened and no pressure was applied. Negative pressure (vacuum) was not recorded by the sensor and therefore not included in the results. Decline of the pulsation vacuum caused collapse of the liner (rest phase) and the pressure at the teat apex increased.

The results for the 3 vacuum levels with the Lely silicone liner (Table 2) show that by increasing the vacuum level, the pressure difference over the liner wall increased during the D phase of pulsation. The increase in teat loading due to a vacuum increase was less at higher vacuum levels, probably because of increased support of the liner. The spatial pressure distribution remained almost unaltered.

Comparison of Different Liners by Measuring on an Artificial Teat

Table 2 shows the results of the liner comparisons. The number of maximum pressure spots was closely re-

Figure 6. Pressure changes at gauge point C9 (Figure 5) applied to the artificial teat in time (s) and the corresponding vacuum level. The vacuum and the pressure during pulsation were not simultaneously sampled. The vacuum curve (gray curve) in this figure is provided as a visual aid for understanding the pressure-vacuum relationship.

Table 2. Liner characteristics derived from dynamic pressure sensor analysis

Liner number ¹	Vacuum level (kPa)	Maximum pressure				Slope		Type graphic ³
		Pressure (kPa)	Gauge point	Duration (ms)	No. ²	Collapsing (kPa/ms)	Opening (kPa/ms)	
1	35	111	9	299	2	1.78	−2.54	A
	44	130	9	244	2	0.89	−2.23	A
	55	138	9	217	2	0.73	−1.78	A
2	44	99	9	190	2	0.99	−1.19	B
3	44	105	9	81	2	1.49	−1.49	C
4	44	153	9	176	2	0.79	−2.60	B
5	44	124	8	258	4	0.23	−0.36	A-B
6	44	174	9	326	3	2.79	−2.23	A
7	44	180	5	312	2	0.24	−0.24	B

¹Manufacturers are as given in Table 1.

²The number of pressure concentrations with a closed liner.

³Type graphic = different graph types of the pressure in time relative to the maximum pressure at the teat end (see Figure 1). Type A = pressure built up and decreased rapidly; type B = pressure increased slowly and decreased quickly; type C = pressure built up rapidly, immediately followed by a slow decrease.

lated to the collapsing pattern and to the design of the liner barrel. Triangular (equilateral) liner barrels led to 3 spots of pressure concentrations around the teat end, 120° separated from each other. No load was measured between those spots because the triangular ribs did not touch the teat. The square barrel design caused 4 pressure concentrations that were not distributed regularly because the liner collapsed like a rhombus. Because of the rounded square corners, pressure was observed all around the teat. In general, when liner types 1, 2, and 3 were compared with liner types 4, 5, and 6, less liner tension (percentage stretch) led to a more uniform distribution of pressures over the teat resulting in less maximum pressure at teat end (Table 2). Because the small diameter of liner type 7, this positive effect was not evident. A liner with smaller mouthpiece depth (Lely Silicone 2) led to a larger part of the liner barrel that effectively supported the teat, thereby inducing a lower maximum pressure at the teat end. Liners with a barrel bore that was matched more closely to the diameter of the teat resulted in better pressure distribution on the whole teat and lower maximum pressures at the teat end. Softer liner material (silicone versus rubber) showed similar results as a rubber liner with less liner pretension. Pressure was more equally distributed, presumably because the silicone material was more flexible and bent better around the teat. This resulted in reduced maximum pressure on the teat end.

Conventional Liner Measurements on a Live Cow Teat

The pressure distribution captured during milking of the live cow teat was comparable to the results of the artificial teat. Remarkably, the (average and maximum) pressures were about 2.5 times smaller on the live cow.

DISCUSSION

In theory, 5 main sources of error could have affected the results of this study: vacuum, sensor bending, sensor thickness, shear force, and the artificial teat. A pilot study showed that the sensor barely registered pressures when only negative pressure (vacuum) was applied. For practical reasons, it was not possible to test the exact effects of sensor bending. When the flat sensor was bent (as it must when adapting to the curvature of the teat apex), part of the sensor was under tension; hence, some sensor output was recorded. During collapse of the liner, the longitudinal curvature of the bending sensor decreased. Sensor output caused by bending was minimal during maximum compressive load at the sites of interest. Moreover, the bending error decreased to almost zero at the beginning of the rest phase before teat load was noticed. At gauge points where the liner did not touch the teat apex during the rest phase, the open liner provided a reference, which was used to establish an offset for the sensor to account for the effect of bending in the longitudinal direction. The transverse bending of the sensor around the teat apex was minimal because of the small sensor size. If higher pressures were recorded because of the sensor thickness, it was most likely because of the increased radius (approximately 7.5%) of the teat-sensor combination for about 1/12 of the teat circumference. This increased stretch at the circumference would be similar for all liners used and, therefore, would not affect comparison between them. We attempted to evaluate the effects of shear as a possible source of error, but the results of simple bench tests were inconclusive and determination of the effect of true shear during the measurements was not assessed. Nevertheless, errors were likely low because a lubricant (silicone spray) was sprayed onto the surface

of the artificial teat to allow each of the test liners to slide more readily around the teat. In summary, the absolute values may be artificially high (by an unknown amount but perhaps <2.5%) because of possible errors due to shear force, allowing us to conclude that these potential measurement errors are within the range of noise levels. The artificial teat used is the fifth source of error. The development of an artificial teat that mimics the properties of a real cow teat is suggested because unwanted cow movements and changes of the teat tissue during milking affect the results. Consistent with the literature, the maximum pressure was always exerted to the end of the artificial teat. These maximum loads varied between 99 and 180 kPa. This was relatively high compared with other reports that determined maximum teat-end pressures in the range of 18 to 35 kPa (Muthukumarappan et al., 1994; Reinemann et al., 1994a,b). Still, when using current technologies, maximum teat-end loads at an artificial teat ranged from 40 to 180 kPa (Gates and Scott, 1986; D. Boast, Avon Rubber, Westbury, UK; personal communication).

The main advantages of the pressure sensor technique used in this study are the high repeatability, resolution (2 sensors per cm²), frequency (100 Hz), and low sensor thickness (0.75 mm). This is an improvement over previous methods used but it still a relatively coarse method. Further improvement could be achieved by increasing the spatial resolution and the data processing.

The spatial pressure distribution pattern at the teat-liner interface of the live cow and the location of maximum pressure were comparable with the artificial teat used. The main difference was that the maximum pressure at the artificial teat was approximately 2.5 times higher. Teat-end pressure is always inversely proportional (linear relation) to the radius of the bent liner around the teat end (Williams and Mein, 1980; Davis et al., 2001; Boast et al., 2008). Artificial teat devices that were too hard experienced higher compressive pressures compared with an actual teat (Gates and Scott, 1986; Reinemann et al., 1994a). The higher compressive pressure was probably because of the rigidity of the artificial teat. When the liner bends around the rigid artificial teat, the radius of the curvature of teat deformation was less than in the case of soft teat tissue (Mein, 1992). Photographs of collapsed liners bending around the artificial teat used in this study and an actual teat showed the radius of the bending liner to be approximately 2.5 times smaller on the artificial teat. If the dynamic requirements of artificial teat characteristics are not met, it would be an option to use an artificial teat that mimics the shape of the teat in a collapsed liner. Although the artificial teat used was too rigid compared with real teat tissue, the difference in absolute pressures was

probably best explained by the difference in curvature. On the other hand, the artificial teat consisted of only 1 type of material, whereas a live cow teat consisted of several different tissue layers (Blowey and Edmondson, 1995). If the linear relation between liner curvature and teat pressures is implemented for all the tested liners, maximum teat load would range from 36 to 74 kPa. Only Boast (Avon Rubber, Westbury, UK; personal communication) found maximum teat pressures in vivo up to 180 kPa, presumably because the spatial resolution of the measurement device was higher because of smaller pressure sensors.

A comparison between calf and liner is difficult because they differ in most if not all aspects. While suckling, the calf exerts a high vacuum level (up to 83 kPa) to the teat (Vennmann, 1953; Happel, 1963; Schoeley, 1989). Only the teat end is exposed to this high vacuum because the rest of the teat is protected by the support of the tongue and palate of the calf. Otherwise, the teat end is only exposed to high vacuums during half of the suckling time because the vacuum drops during the swallowing of milk by the calf (Rasmussen and Mayntz, 1998). During a suckling period a calf changes between 4 teats; hence, 3 teats can recover. In conventional milking the greater part of the teat is exposed to milking vacuum during the B phase and, consequently, the teat tissue swells until it touches the liner wall. The liner imposes a mechanical load to the teat (end) during the D phase of pulsation to unload the teat from the vacuum, to recover the blood circulation of the teat, and to carry off accumulated liquid. During this phase of pulsation, the teat end is still exposed to the full milking vacuum.

The effect of the vacuum level on the maximum teat load was according to the law of diminishing returns. As the vacuum level increased, the change in vacuum level had a relatively smaller influence on the maximum teat load. The same observation was made by Davis et al. (2001).

Liners with a more uniform pressure distribution over the teat resulted in lower maximum teat (end) pressure. Some of these liners (Pro Square, Happel Aktivpulse) were assumed to have better teat condition in practice. Schukken et al. (2006) examined the effect of square liners on teat condition and found an improvement of teat-end callosity thickness and roughness. The special square design of the liner in combination with the smaller liner bore (18 × 22 mm) resulted in improved teat-load distribution and a lower maximum load. The special design of the Happel Aktivpulse provided a vacuum decrease beneath the teat during the D phase, resulting in a maximum teat-end pressure that was applied for only a couple of milliseconds. An enhanced pressure distribution and lower maximum load

was observed with the Lely Silicone 2 liner. This liner was designed for cows with short teats: the mouthpiece depth was less and the liner was mounted in the teat cup under lower tension, so there was a larger part of the liner barrel that effectively supported and massaged the teat.

CONCLUSIONS

Pressure distribution measurements at the teat–liner and teat–calf interfaces demonstrated certain liner characteristics and teat loading patterns during milking or calf suckling. The vacuum decrease during the swallowing of milk by the calf provided a brief period for the teat to recover blood circulation and relieve congestion and edema in teat tissues. All types of liners exert higher pressures to the surface of the teat apex compared with calf suckling. Liner differences had a major effect on teat loading. Loading patterns seem to be fixed because of magnitude, duration, and distribution of the teat pressures. Liners that distribute the pressures more equally over the teat surface show lower maximum pressure on the teat end. This mechanism could explain the enhanced teat condition experienced in practice from such liners.

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