

FORCES APPLIED TO THE BOVINE TEAT BY THE TEATCUP LINER DURING MACHINE MILKING

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Abstract: Five different techniques to measure the effective compressive load, or the spatial distribution of pressures applied to artificial and live teats by the teatcup liner, are described. Three techniques warrant further development. Compressive load applied to the teat was increased by greater pressure difference across the teatcup liner, and by higher liner tension. The relationship between applied compressive load and material hardness was nonlinear.

1. Introduction

The main purpose of pulsation is to limit the development of congestion and edema in the teat tissues during machine milking. Pulsation consists of alternate collapse of the teatcup liner beneath the teat when air at atmospheric pressure is admitted to the pulsation chamber of the teatcup, and reopening as the pulsation chamber is evacuated. The collapsed liner applies little or no force to the teat barrel above the teat apex and does not close the teat sinus at any stage of milking because there is little or no pressure difference between the teat sinus and the teatcup pulsation chamber. However, liners normally compress the teat apex during the collapse phase of each pulsation cycle. The compressive force results from the relatively stiff liner, which is usually in longitudinal tension, bending around the teat apex in the longitudinal and transverse planes (2).

Compressive load is generally expressed in terms of the pressure, above atmospheric, applied to the teat apex by the closed liner. This is due, in part, to the complexities of measuring the force and the area over which the force is applied. This study describes:

- 1) Five different techniques to measure the effective compressive load and spatial distribution of pressures applied to artificial and live teats by a range of commercial and experimental teatcup liners;
- 2) some effects of varying the pressure difference across the teatcup liner, liner tension and material hardness, on the compressive load applied to the teat.

2. Materials and Methods

2.1 Force measurements using commercial, thin-film sensors

Several thin-film commercial force sensors were tested for measuring the average and distribution of compressive load applied to the bovine teat by different teatcup liners. Bending of these sensors around the teat introduced significant error in the force measurement. Because these sensors also exhibited a high degree of hysteresis, we concentrated on developing alternative techniques.

2.2 Pressure measurements using an extruded clay ribbon

A ribbon of clay 0.6 mm in diameter was extruded from a plunger apparatus and placed between two sheets of paraffin film. Known loads were applied to the clay ribbon. The resulting width of the ribbon was measured using an image processing system fitted to an optical microscope. Ribbon width correlated well with applied pressures up to 50 kPa using a third-order polynomial ($R^2 = 0.98$). Measurements were made by placing the paraffin film and clay ribbon between the liner and a hard plastic teatcup plug (1) while the liner was stopped in its open position. The liner was then pulsated for 10 cycles, stopped open, and the clay strip removed carefully. The width of the deformed specimen was measured along its length using the image processing system.

The maximum pressure was applied within 1 to 2 mm from the tip of the teat and the applied pressure decreased progressively over the upper 3 to 4 mm of the teat apex. Both the maximum pressure and the ratio of the maximum to the average pressure applied to the hard plastic plug were higher than for a softer live teat, as expected. Because this technique was difficult to apply with living teats, it was not developed further.

2.3 Pressure distribution measurements with a flat tube and excised teat

A simple pressure sensor was constructed by heat sealing two strips of polythene film together to form a flexible flat tube 2 mm wide, 30 mm long and 1 mm thick (Figure 1a). The sealed edges were made 2-3 mm wide to minimize pressure measurement errors due to edge effects. A stiff-walled nylon tube of 1 mm bore and 1 mm wall thickness was inserted into one end of this flat tube. The connection was sealed with silicon glue and tied with surgical silk. The other end of the rigid tube was connected to a closed reservoir of colored liquid. Air pressure in the reservoir was varied by means of a hand-operated pump.

An excised teat was inserted into a transparent teatcup shell and liner with the flat tube sensor placed between the teat and liner along the centre line of the plane of collapse of the liner barrel. The air pressure in the reservoir was raised in steps of about 5 kPa while the hydrostatic head remained constant at less than 1 kPa. The pressure in the reservoir was assumed as the equilibrium pressure between the opposing surfaces of the teat and liner at the lower margin of the liquid in the flat tube sensor.

2.4 Measurement of average compressive load on an artificial teat sensor

A method described by Mein (3) was adapted to measure pressure changes within a liquid-filled, floppy, non-distendable artificial teat. The teat sensor was made from a standard plastic teatcup plug (1), a surgical glove finger, and a leather glove finger (Figure 2). The teatcup plug was cut off 25 mm above its tip and the open end shaped by heat and pressure to form a smooth ellipse. The major and minor diameters of this ellipse, 21.6 and 16.5 mm, were chosen to simulate the shape of the teat apex in a collapsed liner. A surgical glove finger was inserted into the leather finger and tied to a rubber stopper. The whole system was pressed into the plastic teat so that the flexible glove finger protruded 14 mm from the end of the hard plastic teat plug. The other end of the stopper was connected to a pressure transducer and a water reservoir and all air was bled from the system. Measurements were made in the following way.

- 1) The artificial teat sensor was inserted into the teatcup assembly and pulsated normally for 6 cycles with the 3-way valve sealing the sensor sinus. This allowed the sensor to be drawn into the liner and reach an equilibrium position, thus reducing shear forces on the sensor surface. Liner was then held open by stopping the pulsator so that the pulsation chamber vacuum (PCV) = liner vacuum (LV) = 40 kPa. A water reservoir was connected to the teat sensor by opening the 3-way valve. The sensor pressure was set to about +4 kPa to represent intra-mammary pressure during milking.

- 2) The 3-way valve was then adjusted to seal the teat sensor volume and disconnect the water reservoir. The liner was collapsed by switching PCV to atmospheric pressure (with LV held constant at 40 kPa) and the sensor pressure recorded as P1.
- 3) The liner was then opened by disconnecting the liner vacuum so that $LV = PCV =$ atmospheric pressure, and the new sensor pressure recorded as P2. The change in sensor pressure, $P1 - P2$, was taken as a measure of the effective compressive load applied by the collapsed liner to the teat.

2.5 Measurements with live teats during milking

Measurements of the pressure difference across the liner wall, at which milk flow just starts or stops can provide a dynamic test for the compressive load applied by a particular liner to any teat. The point at which the milk flow is just stopped by the collapsing liner occurs when the distending force due to LV is just offset by the compressive force of the closing liner. Starting from this equilibrium point, the maximum load applied to the teat is about equal to the incremental change in air pressure in the pulsation chamber when this chamber is at atmospheric pressure (2, 4).

A hand-operated vacuum pump and digital gauge were connected into the long pulse tube (between the pulsator and the front pair of teatcups) by means of a 3-way valve. The teatcups were applied to the udder for 1 minute of normal milking. The liner was then stopped in its closed position by opening the pulsation chamber to atmosphere with the 3-way valve. The pulsation chamber was then connected to the hand pump via the 3-way valve. PCV was increased slowly using the hand pump and the vacuum at which milk just started to flow from the teat was read from the digital vacuum gauge. This measurement procedure took about 30 s to perform. Normal milking was then resumed.

The right front (RF) and right hind (RH) teats of 20 cows were milked with any one of a series of commercial and experimental liner types. The left side teats were milked with the standard teatcups normally used in the dairy, to serve as half-udder controls.

3. Results and discussion

3.1 Pressure distribution measurements using the flat tube sensor

When the liquid reservoir was at atmospheric pressure, liquid in the flat tube sensor flowed to within 10 mm of the tip of the excised teat. The pressure within the sinus of the excised teat was also at atmospheric pressure. This result confirms that the undeformed liner applies little or no pressure to the teat barrel, and that the pressure between the contact surfaces is essentially the same as the sinus pressure. As the air pressure in the liquid reservoir was raised in increments of about 5 kPa, the liquid in the flat tube sensor moved down the teat apex towards the lower margin of contact between the teat and liner. The relationship between contact pressure and distance from the lower margin of teat/liner contact was approximately linear as illustrated in Figure 1b.

3.2 Comparison between artificial teat sensor and live teat measurements

Effective compressive load measured after 1 min of milking with living teats were closely correlated with those obtained with the artificial teat sensor (Figure 3). The correlation coefficient of this relationship was 0.92. The effective compressive load measured with the artificial teat sensor was similar to that measured with live teats. Response characteristics of the teat sensor were dependent upon the internal pressure, shape, volume and materials used for the active portion of the sensor. The high correlation coefficient indicates that the present sensor and

methodology produce a reliable indication of the relative compressive load applied to live teats by conventional liners with circular barrels. Furthermore, for a given sensor the results were highly repeatable and the relative ranking of compressive load applied by liners was not changed by minor variations in sensor pressure, and geometry. Differential sensor pressures obtained with liners having noncircular cross sections tended to be higher than those for circular liners.

3.3 Effect of liner vacuum, liner tension and material properties

The effects of liner vacuum level, and liner tension, on compressive load measured with the artificial teat sensor are shown in Figure 4. Increasing liner vacuum or liner tension increased the compressive load applied to the teat. The relationship between material hardness and compressive load applied to living teats is shown in Figure 5.

A similar relationship is evident between liner wall thickness and compressive load (Le Du & Mein, in preparation). This relationship is not surprising because an infinitely thin-walled liner cannot apply any pressure to the teat above the atmospheric air pressure in the pulsation chamber. On the other hand, a liner that is too thick to be collapsed by the pressure differences normally applied in a teatcup cannot apply a compressive load to the teat. Between these two limits, compressive load should increase with increasing wall thickness up to some maximum level. Similar physical interactions will apply to the effects of changes in rubber hardness and, perhaps, to increasing liner tension as well.

4. Conclusions

Three techniques to estimate the effective compressive load applied to the teat by the collapsed liner warrant further development. One technique can be applied readily at cow-side. The other two are laboratory techniques at this stage. The effective compressive load values obtained with an artificial teat sensor and living teats were closely correlated (correlation coefficient of

0.92). Increasing liner vacuum and liner tension increased the compressive load applied to the teat. Compressive load is applied only to the apex of the teat where the liner bends around the teat. Maximum pressure is applied near the lower margin of contact between the teat and liner in the centre of the plane of collapse.

References

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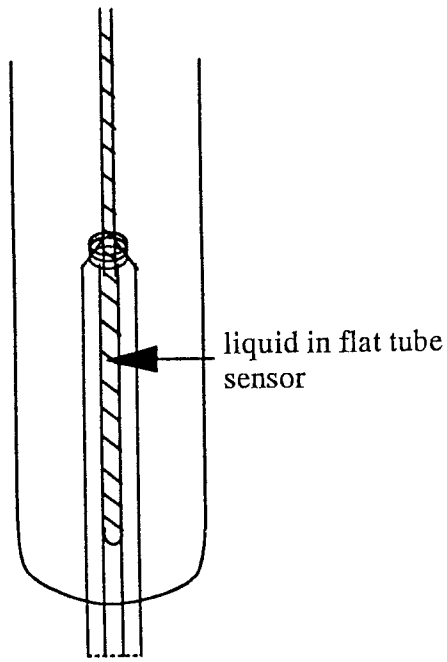


Fig. 1a Diagram of flat tube sensor between excised teat and transparent teat-cup liner

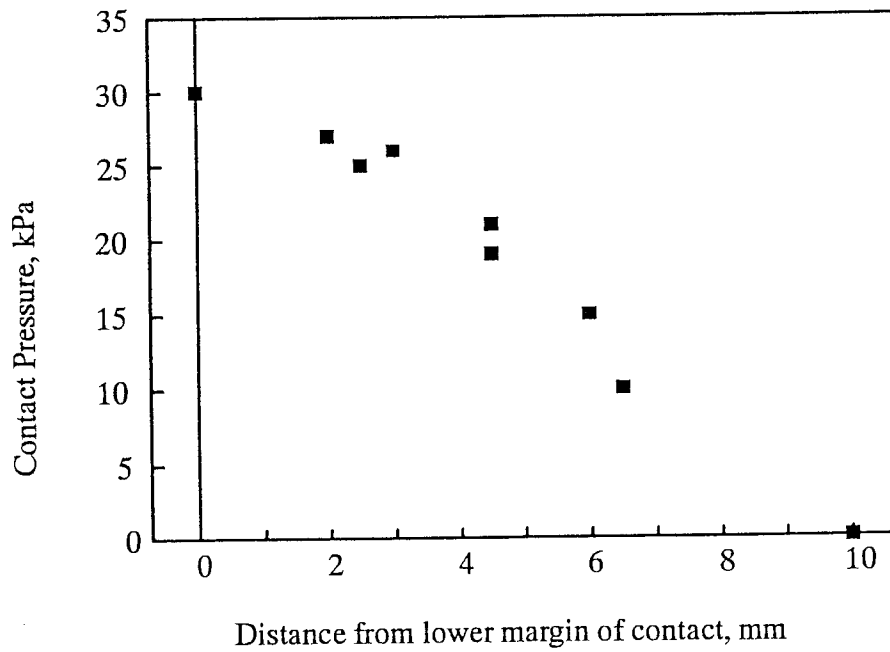


Fig. 1b Relationship between contact pressure in flat tube sensor and distance from lower margin of contact between teat and collapsed liner

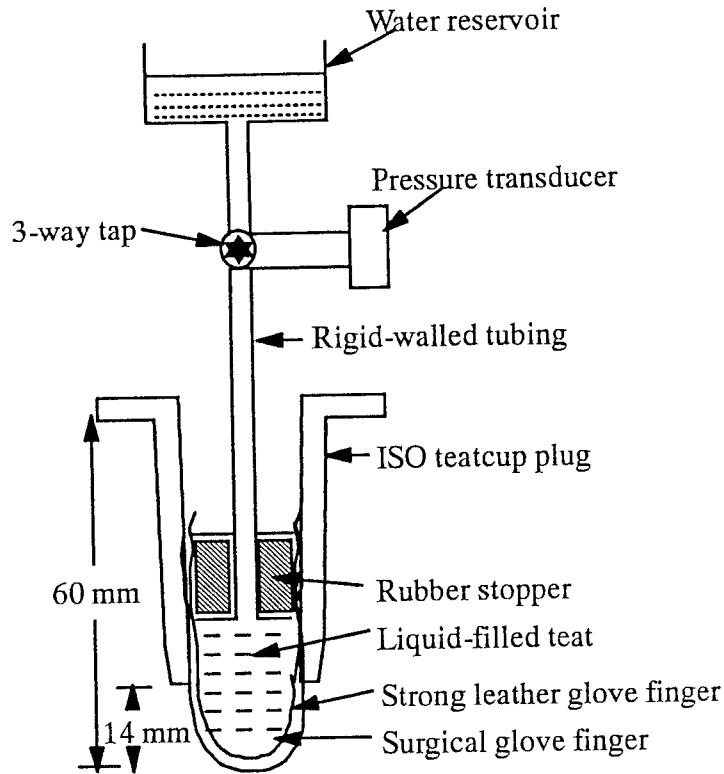


Fig. 2 Artificial teat sensor used to measure effective compressive load applied by the collapsed liner

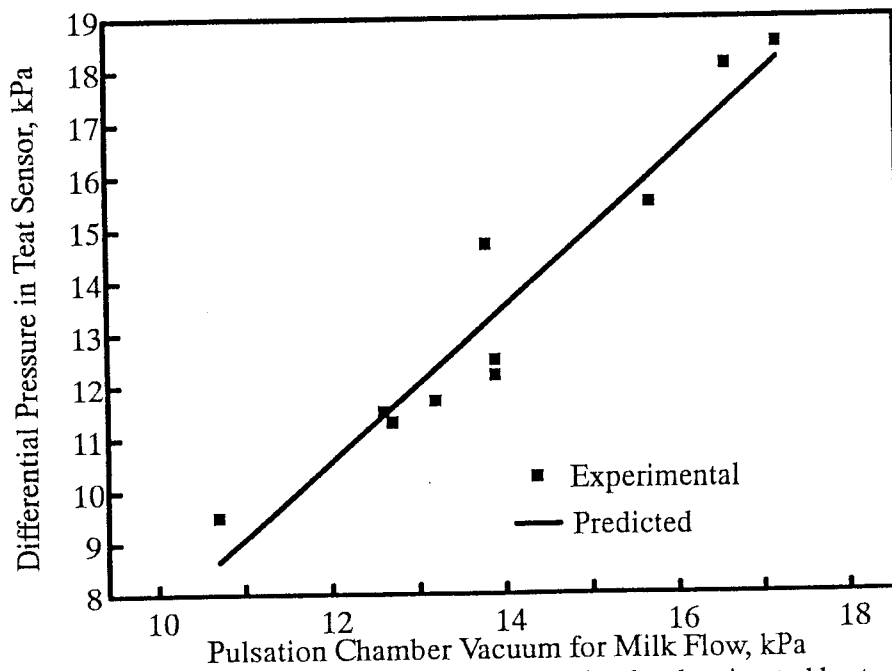


Fig. 3 Comparison between the effective compressive load estimated by two different methods: 1) differential pressure within an artificial teat sensor and 2) pulsation chamber vacuum at which milk just starts to flow from live teats

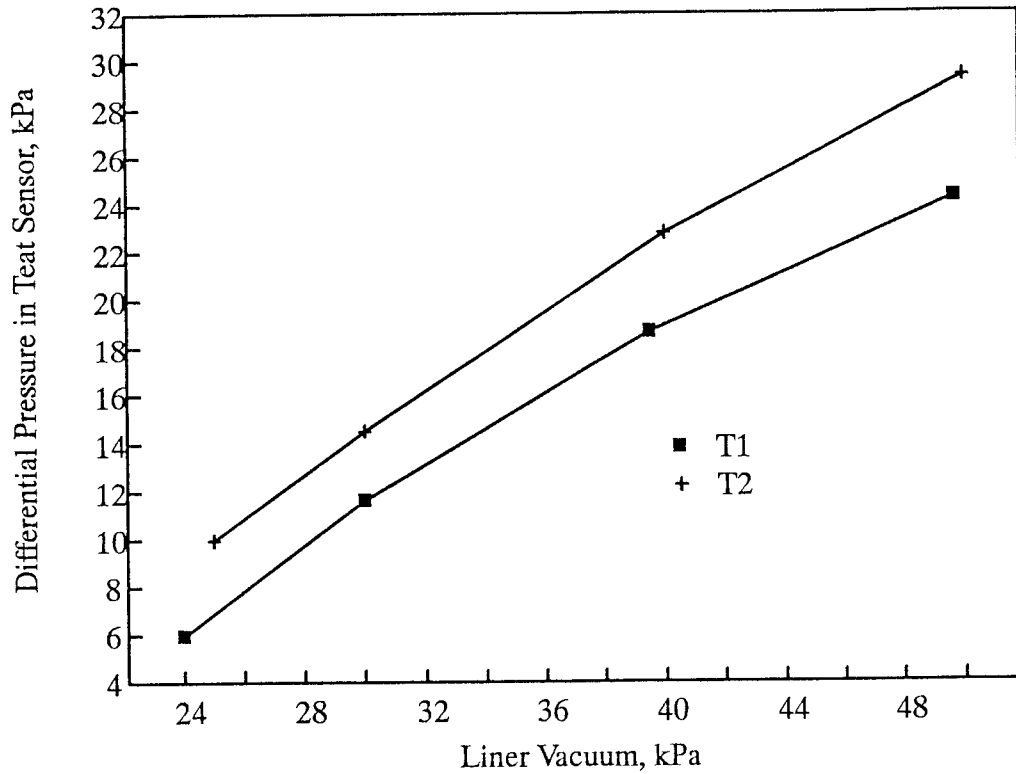


Fig. 4 Effect of liner vacuum on compressive load (estimated by differential pressure in artificial teat sensor) applied by a liner mounted in its teatcup shell at two different tensions (T1=58N and T2=74N)

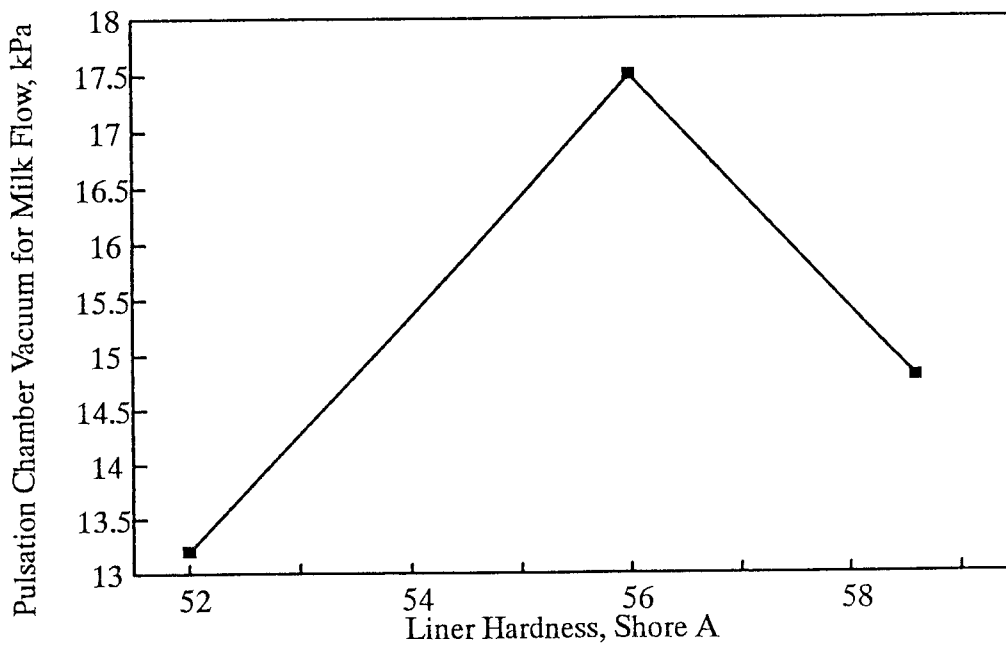


Fig. 5 Curvilinear relationship between compressive load (estimated by the PCV when milk flow starts) and varying material hardness for one type of liner