Development and Testing of a Device to Measure Compressive Teat Load Applied to a Bovine Teat by the Closed Teatcup Liner

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Abstract. *A measurement device was developed for measurements of the compressive load applied to a teat by the closed teatcup liner. The device consisted of a load cell covered with a material to simulate the biomechanical properties of teat tissue. Two materials were compared against excised teat tissue: gum rubber and a soft gel-like material. Compressive load measurements were conducted on five different liners to assess the response of the device with the individual materials. Device response to changes in liner tension, wall thickness and penetration depth was favorable. The gel-like material performed statistically similar to teat tissue in the liner tests. Material compression tests indicated that for input strains under 37%, the gel deformed statistically similar to that of a teat. The gel material seemed to simulate teat tissue better than gum rubber and is a recommended alternative to teat tissue as a sensor covering material on the teat sensor device developed in this study.*

Keywords. *Teat, Liner, Massage, Pressure, Collapse, Load, Measurement*

INTRODUCTION

The purpose of the milking liner is to provide relief to the teat from the milking vacuum. When the pulsation chamber is brought to atmospheric pressure, the liner closes and applies a compressive load to the teat end as the tensioned liner bends around the teat apex (Mein et al. 1987). This compressive load is a function of the pressure difference between liner vacuum and pulsation chamber vacuum, liner tension, liner wall thickness, liner hardness (Hamann et al. 1994; Muthukumarappan et al. 1994; Reinemann et al. 1994) and teat penetration (Szlachta 1985).

The specific objective of this study was to develop an improved device for measuring the compressive load applied to the teat by the closed milking liner. Many attempts have been made to measure the compressive load of the liner. These attempts range from the use of sophisticated ultrasound techniques to the use of simple pressure or load transducers. Thompson (1978) proposed the use of an ultrasonic transducer to record teat position during milking to relate teat deformation to the force upon the teat during milking. A 1978 study by Balthazar and Scott pioneered modeling teat deformation by finite element analysis; unfortunately, this study did not measure compressive load directly. A similar study by Rønningen (1992) used dynamic stereophotogrammetry techniques to produce a three-dimensional image of the liner closed upon the teat. However, Rønningen stated that more work is necessary to compute teat load from the model.

Mein et al. (1987) measured teat canal pressure directly by use of a catheter tip inserted into a live teat during milking. Williams and Mein (1987) measured the pressure difference required for retrograde milk flow using a cannula attached to the teat orifice. Muthukumarappan et al. (1994) used the vacuum difference across the liner at initiation of milk flow from the teat to estimate compressive load.

Gates and Scott (1986) measured the compressive load by mounting pressure transducers on the inside wall of the liner. Thompson (1978), Gates (1984), Muthukumarappan et al. (1994) and Reinemann et al. (1994) measured compressive load by inserting a thin pressure sensor between the teat and liner. These measurements are difficult to make as it is challenging to achieve similar sensor placement for various teats and liners.

Some studies have involved construction of an artificial teat that acted as a pressure vessel (Caruolo 1983; Gates 1984; Szlachta 1985; Muthukumarappan et al. 1994; Reinemann et al. 1994) or contained a load cell (Adley and Butler 1994). The advantage to constructing a portable teat-like device is it allows one to easily test a variety of liner-shell combinations, unlike a device that is mounted on the liner.

It has been a challenge to design a device that deforms in the same way as a live teat and also has the ability to accurately measure compressive load. Artificial teat devices that are too hard will experience a higher compressive load than an actual teat (Gates and Scott 1986; Reinemann et al. 1994). The higher compressive load is due to the lack of deformation of the rigid artificial teat as compared to a real teat. As the liner bends around the rigid artificial teat, the radius of curvature of teat deformation is less than that of a soft teat, resulting in a greater compressive load for the radius of curvature of a given liner; refer to Figure 1 (Mein 1992). Positioning of the artificial teat device in the liner has also posed a problem, as the compressive load varies with teat penetration (Caruolo 1983; Gates and Scott 1986; Adley and Butler 1994).

$$pR = Pr$$

Where:
R = radius of curvature of liner around teat (mm).
p = pressure (kPa above atmospheric) between liner and teat.
r = radius of curvature of liner just under the teat (mm).
P = pressure difference across liner
just under the teat (kPa)

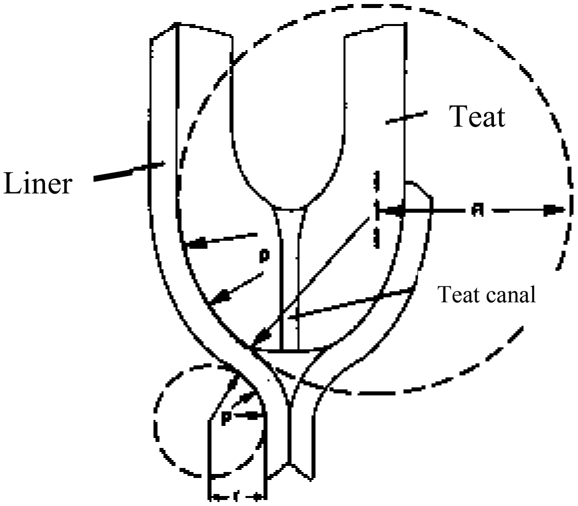

Figure 1. Illustration of liner bending around the teat apex (Bramley et al. 1992 pp. 121,122).

Previous studies have shown that compressive load of the liner is greatest at the teat apex and is nearly negligible along the teat barrel (Mein 1978; Gates 1984; Reinemann et al. 1994). Compressive load increases with liner tension and stiffness (Szlachta 1985; Mein et al. 1987; Muthukumarappan et al. 1994) and pressure difference across the liner wall (Balthazar and Scott 1978; Muthukumarappan et al. 1994).

Liner loads measured with a pressure difference of 50 kPa range from 10 to 22 kPa (Williams and Mein 1980; Mein and Williams 1984). Thompson (1978) found liner loads ranging from –7 to 50 kPa with a pressure difference of 37 kPa. Szlachta (1985) reports a liner load of 11 kPa for teat penetration of 75 mm and a pressure difference of 45 kPa. Reinemann et al. (1994) reports contact pressure between the teat and liner of 30 kPa at the teat end. Gates and Scott (1986) report a range of teat load of five different liners from –22.5 to 37.5 kPa with a maximum measurement of 53.5 kPa using an artificial teat. Caruolo (1983) measured compressive load for various liner/shell combinations and found a range of 8.9 to 29 kPa in compressive load. Mein et al. (1987) suggests a compressive load of 8 to 12 kPa for adequate massage.

This work describes the design and testing of a device to measure compressive load applied to a teat by the closed milking liner as compared to a "comparison only" device. In common with most previous attempts to measure compressive load, we have expressed our results in terms of the pressure (rather than force) applied to the teat.

MEASUREMENT OF MATERIAL PROPERTIES OF TEAT TISSUE

An interesting Ph.D. thesis on the biomechanics of the teat-liner interaction was completed by R.S. Gates in 1984. This study involved material testing of fresh excised teat tissue in both tension and compression. Compression tests involved round, 18-mm diameter samples punched from the cylindrical portion of the teat. It appears from the literature that the sample contained the outer skin and inner tissue of the teat. The tissue samples were then placed in Kroebs Ringer solution and held at 37 °C to simulate *in vivo* conditions before testing. Compressive load tests were conducted and load-deformation data were recorded. The minimum and maximum Young's moduli and Poisson's ratios were determined from two samples each from 11 teats. Gates reports a Young's modulus ranging between 35.7 to 124.2 kPa at 5% strain in unconstrained compression of a sample of teat tissue. He also found Poisson's ratio ranging from 0.4560 to 0.4997 for the teat tissue. The methodology of determination of Young's modulus and Poisson's ratio in this work followed that of Gates (1984).

Balthazar and Scott (1978) conducted separate compressive load tests on three layers of freshly excised teat tissue: skin, collagenic and elastic fibers and the teat cistern wall. Balthazar and Scott used rectangular samples, 2.5 cm by 1.25 cm, from each layer from 7 udders. A total of 219 samples were tested and used to construct one representative stress-strain curve for each layer. The outer skin layer was found to exhibit the greatest stiffness. Stress at 25% strain was found to be approximately 15 kPa from the stress-strain curves in the literature; Young's modulus and Poisson's ratio were not given.

MATERIALS AND METHODS

MATERIAL TESTING OF SENSOR COVERINGS

An Instron (MTS Synergie 200 with 1 kN load cell, accuracy 1% of full scale) was used to conduct a compression analysis of the three sensor coverings; the samples of rubber and gel tested were the actual pieces of the material mounted on the top and bottom of the sensor during testing of the liners. The intact excised teat tip tested had been frozen and was unthawed and immediately tested before the tissue dried out. Each sample, with one-half surface area approximately equal to 295 x 10^{-6} m^2, was tested in unconstrained compression to a strain of 50%. Load and deformation were recorded with a sample rate of 10 Hz during compression. A surface detection load of 0.05 N was used; the material was compressed at 0.1 mm/s. Given the sample surface area of applied load (one-half the entire surface area) and initial sample height, the engineering stress and strain (or fractional deformation) were calculated.

The method of Gates (1984) was used to determine Young's modulus and Poisson's ratio for each material at a 5% strain. Gates determined the maximum and minimum Young's modulus at 5% strain and used this in a ratio with the maximum and minimum Young's modulus for a constrained compression. The maximum and minimum values of Young's modulus were determined using strains between 5 and 6%. There were approximately 15 readings at this strain level for all materials. The equation used by Gates (1984) and used in this work is shown in Equation 1 below:

$$\frac{E(\varepsilon)}{E_c(\varepsilon)} = \frac{(1-2\nu)(1+\nu)}{1-\nu} \tag{1}$$

where: $E(\varepsilon)$=Young's modulus (kPa), or slope of the stress-strain curve, at 5% strain

$E_c(\varepsilon)$=Young's modulus (kPa) for constrained compression, from work of Gates (1984).

$E_c(\varepsilon)_{max}$= 24.1 x 10^3 kPa $E_c(\varepsilon)_{min}$= 524 kPa

ν=Poisson's ratio (kPa/kPa)

CONSTRUCTION OF THE DEVICE

The device to measure compressive load of the closed liner on the teat is illustrated in Figure 2.

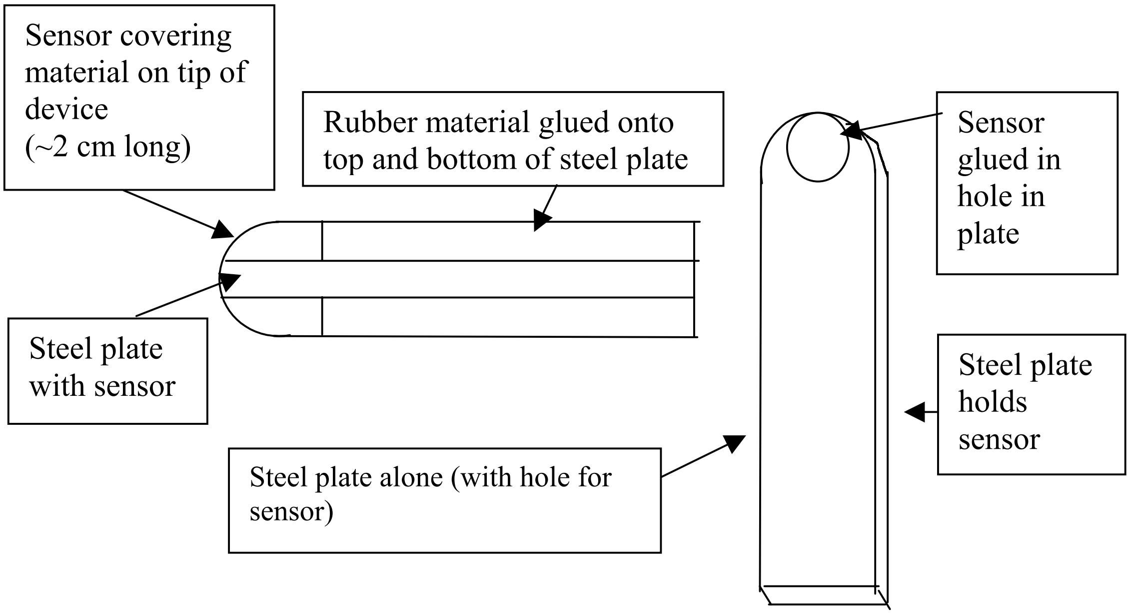

Figure 2. Compressive teat load measurement device.

Adley and Butler (1994) used a similar device made of aluminum with a load cell at the lower barrel of the teat. Unlike Adley and Butler, the device used in this study was developed to deform similar to a live teat and measure the force applied near the teat apex. A miniature load cell (Entran, model ELFS-B3-100N-/V10, 12.7 mm diameter) was mounted in a steel plate 2.4 mm (0.1 in) thick by 20 mm (0.8 in) wide. The load cell was mounted in the steel plate so that its sensing surface was flush with the surface of the steel plate and was located approximately 79 mm (3.1 in) from the end of the steel plate.

A rubber material was glued on each side of the rigid plate. A material to cover the sensor that deformed similar to teat tissue was sought. An artificial material was preferred, as actual teat tissue would change in physical properties with time and would need to be replaced after every test. Changing the tip of the sensor with fresh teat tissue before each test would not only be cumbersome, but would change the sensor completely as Balthazar and Scott (1978) found that material properties vary between teats. Two artificial materials, natural gum rubber and a gel-like material from the inside of a wrist pad for a computer keyboard, were tested by replacing the tip (~2 cm long) covering the sensor only. The material "tips" were held on the sensor by placing a snuggly fitting latex glove finger over the entire device. Both materials were calibrated and used to measure compressive load on a variety of liners. Lastly, the intact tip of a freshly excised teat was used as a sensor covering for a comparison. It is important to note here that the intact "tip" of an excised teat used in this work included all four layers of teat tissue specified by Balthazar and Scott (1978): "...a thin skin layer, a layer containing collagenic and elastic fibers, a fiber layer and the teat cistern wall." A cross-section of the "intact teat tip" tested on the compressive teat load measurement device is shown in Figure 3.

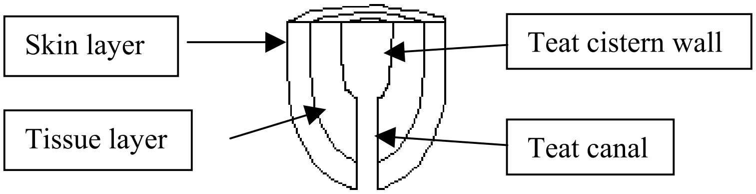

Figure 3. Enlarged cross-section view of "intact teat tip" used as a sensor covering.

CALIBRATION OF THE DEVICE

The device was calibrated in a pressure chamber with each material covering before testing of each material. A bleed valve was used to regulate the air pressure applied to the pressure chamber; a tee-piece was used to continuously monitor the air pressure via a mercury manometer. A similar system was used to apply positive pressure to the pulsation chamber during liner testing and is shown in Figure 4.

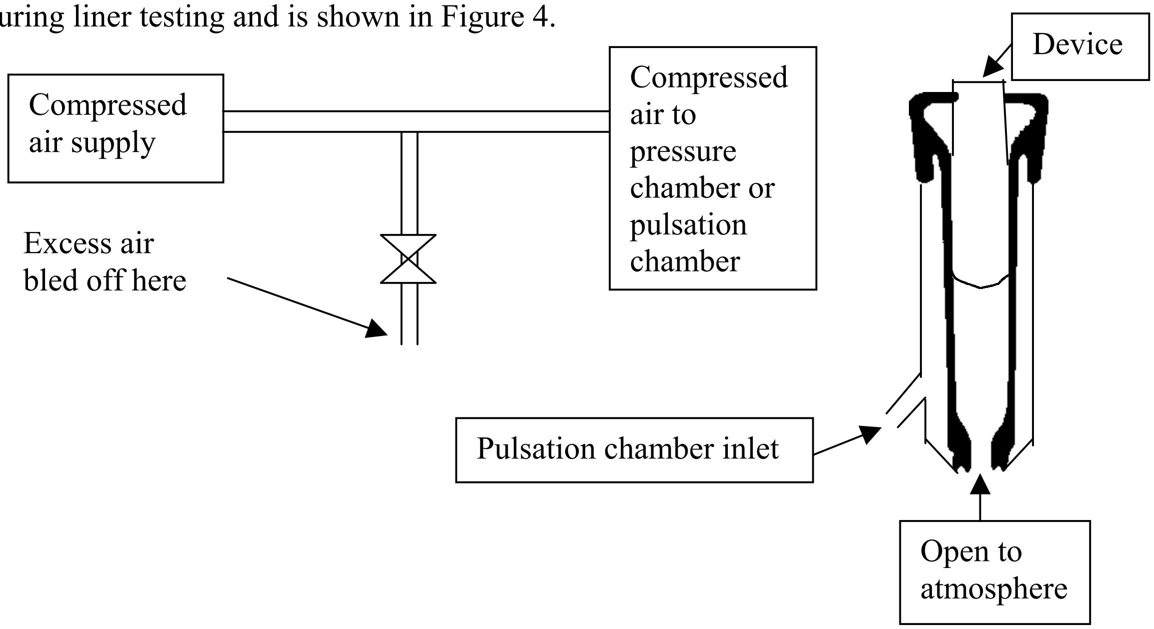

Figure 4. Regulation of compressed air during device calibration and compressive load tests.

A zero reading was first taken with the device inside the pressure chamber but open to atmosphere. The pressure chamber was then sealed and the change in sensor voltage output from the zero point was recorded from 0 to 61 kPa (0 to 18 inHg).

COMPRESSIVE LOAD TESTING OF VARIOUS LINERS

The compressive load device was tested on three commercial and two modified liners: DeLaval DeLatex 01, DeLaval DeLatex 01 with a thin (2 mm) wall, Conewango 1D 01A, TLC D2000 triangular bore, and a Bou-Matic R2CV with a thin (1.5 mm) wall. The thin wall liners were made by mounting the liners in a lathe and grinding the outer surface of the liner barrel to achieve the thin wall. One piece liners were used with a standard Alfa Laval 06 shell that measured 142 mm and a modified shell shortened to 126 mm to produce a lower liner tension. The Bou-Matic liner was used with a Bou-Matic Visi-Shell mounted at the standard second tension ring.

The liners were tested by applying compressed air to the pulsation chamber of the teat cup shell to compress the liner upon the device. Vacuum was not used to collapse the liner as this had resulted in past load cell damage. The liners were tested in the following manner: first, a voltage output reading of the sensor was taken at atmospheric pressure outside of the liner. Next, the collapse plane of the liner was determined by applying compressed air to the pulsation chamber of the teat cup shell. Vacuum at 42 kPa (12.5 inHg) was then applied to the pulsation chamber to open the liner for ease of insertion of the device. The device was then inserted 72 mm (2.8 in) into the liner with the rigid plate, containing the load cell, positioned normal to the plane of liner collapse; the vacuum was then removed. The liner was then collapsed upon the measurement device by applying positive air pressure from 0 to 51 kPa (0 to 15 inHg) to the pulsation chamber via the set-up illustrated in Figure 4. The change in sensor output voltage was recorded. The voltage change due to the applied air pressure, which was known from calibration in the pressure chamber, was subtracted from this result.

RESULTS & DISCUSSION

MATERIAL TESTING OF SENSOR COVERINGS

All three sensor-covering materials were compressed, unconstrained, with an Instron to determine the material response for each material. The stress-strain curves for each material is shown in Figure 5 for a 50% strain.

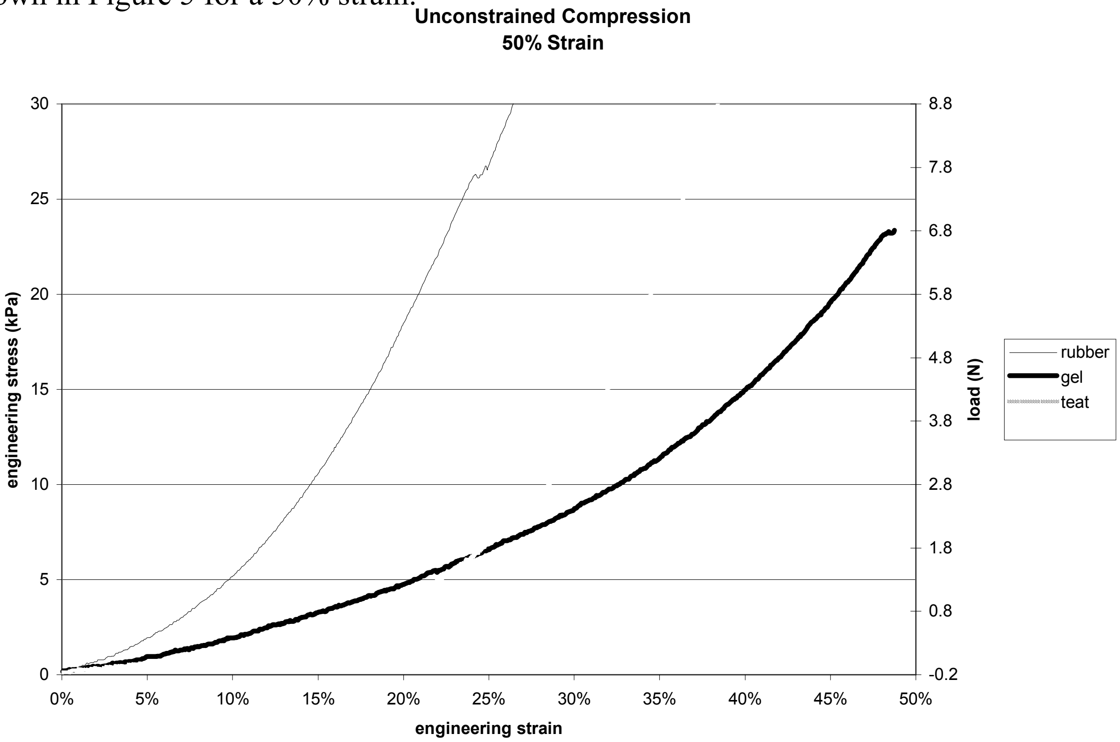

Figure 5. Stress-strain curves for the sensor covering materials tested.

It can be seen from Figure 5 that at a strain of 23 to 24%, both the gel and teat have a stress of 6 to 6.5 kPa. At strains higher than 24%, the material characteristics of the excised teat tissue fall between the rubber and the gel material; the teat also begins stiffening, or begins to increase in output stress due to input strain.

The rubber material exhibits a larger Young's modulus (slope of stress-strain curve) than the gel, supporting the hypothesis that it is a harder material. The gel seems to deform similar to the teat tissue up to a strain of about 25%. At strains greater than 25%, the gel continues to deform while the teat begins to stiffen due to supporting tissues, such as the skin layer and collagen fibers. It must be noted that these tests were conducted on a thawed intact teat tip (refer to Figure 3). The freezing and thawing of the tissue may have changed the physical properties.

The maximum and minimum Young's modulus was determined at a 5% strain to calculate the maximum and minimum Poisson's ratio at this strain. Using Equation 1 and the maximum and minimum constrained moduli from Gates (1984) yielded the following (Table 1):

Table 1. Material properties at 5% strain for sensor coverings.

	Rubber	Gel	Teat	Gates (1984)
E_{min} (kPa)	48.10	49.46	49.46	35.7
E_{max} (kPa)	152.54	50.85	150.29	124.2
ν_{min} (kPa/kPa)	0.4440	0.4831	0.4449	0.4560
ν_{max} (kPa/kPa)	0.4997	0.4996	0.4996	0.4997

Young's modulus and Poisson's ratio for the teat tip were similar to that found by Gates in 1984 for a punched sample of teat tissue. Evaluating the sensor material at only the 5% strain level, the rubber material is more similar to teat tissue than the gel. However, it is plausible that the sensor covering materials were under strains greater than 5% during compression testing of liners.

CALIBRATION OF THE DEVICE

Change in sensor voltage with applied pressure was regressed through the origin. All three materials tested had approximately the same slope of the regression equation, as shown in Table 2. The contribution of the applied air pressure upon the sensor could then be calculated for each material.

Table 2. Response of Sensor Covering Materials from Calibration in the Pressure Chamber.

Material	Response (V/kPa)	1/Response (kPa/V)
Teat Tissue	0.0173	57.67
Rubber	0.0169	59.15
Gel	0.0168	59.41

The sensor material covering did have a small effect upon its response during calibration in the pressure chamber. The three individual calibration curves were used to compute the sensor response due to applied air pressure during the liner compression tests.

MEASUREMENTS OF COMPRESSIVE LOAD OF LINERS: EFFECT OF SENSOR COVERING

The liner contribution of the sensor response is shown in Figure 6 for four different liners and three different sensor coverings. The liner contribution was the remainder of the total voltage change after the contribution from the air pressure had been removed.

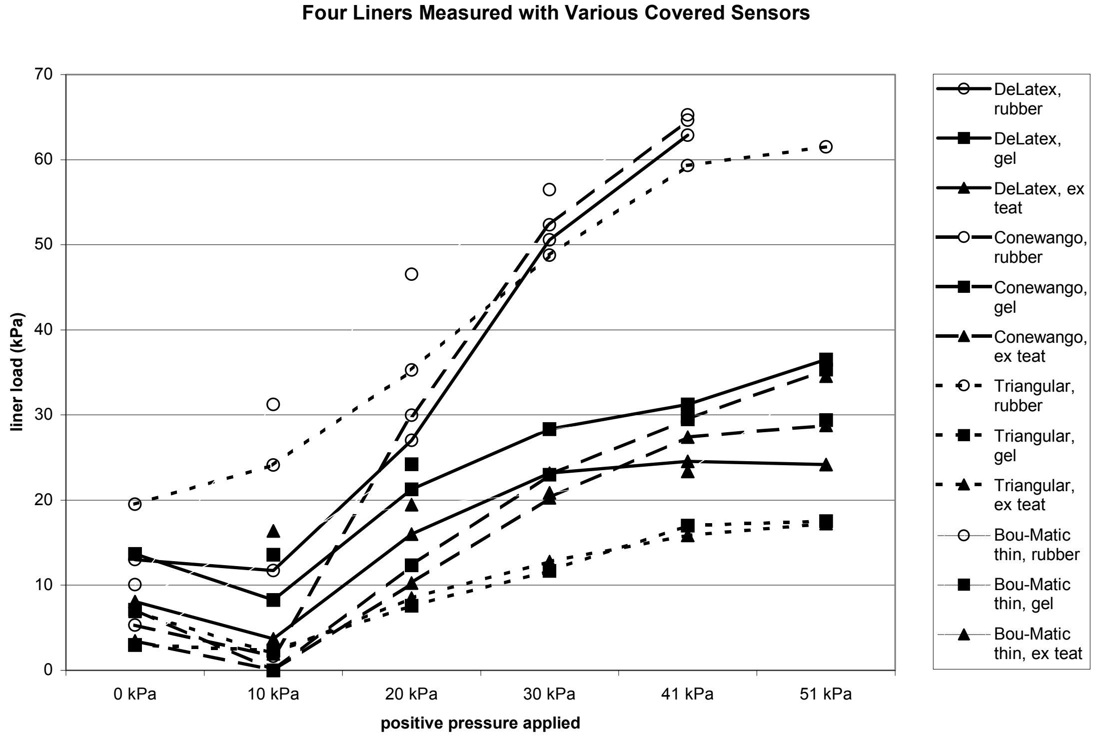

Figure 6. Liner load (kPa) for four different liners and three different sensor coverings. Liners are denoted by line styles, sensor coverings are denoted by marker styles.

Statistically significant ($p<0.05$) differences were found between liner loads of the rubber covering and gel, as well as between the rubber and excised teat at applied air pressures of 20 through 41 kPa (6 through 12 inHg). No significant differences were found with a paired Student's t test at the $\alpha=0.05$ level between the liner load readings of the gel and excised teat tissue for any applied air pressures.

Similar to the findings of Balthazar and Scott (1978), Szlachta (1985) and Muthukumarappan et al. (1994), the compressive load was positively correlated with the pressure difference across the liner. Minimum compressive loads of the four liners tested range from 0 to 37 kPa (0-11 inHg) as measured with the gel sensor covering over pressure differences of 0-51 kPa. Using the applied pressure of 41 kPa (12 in Hg) and results from the gel and teat tissue sensor covering as a comparison point, the four liners tested had a compressive load of 16-31 kPa (5-9 inHg). This finding is about 12 kPa higher than that found by Williams and Mein (1980) and Szlachta (1985) at pressure differences of 50 kPa and 45 kPa, respectively. However, this finding is within range of Thompson (1978), Caruolo (1983), Mein and Williams (1984), Gates and Scott (1985) and Reinemann et al. (1994).

Referring back to Figure 5, material tests supported the hypothesis that the rubber was harder than excised teat tissue. Figure 5 also illustrates that the gel deformed similar to the teat at strains up to 37%. The liner tests, shown in Figure 6, reflected the differences in the material characteristics of the rubber and gel. The gel produced compressive teat load readings similar to the excised teat while the harder rubber material produced higher reading as expected.

DEFINITION OF LINER LOAD

The load upon the sensor (or teat) in the liner was hypothesized to be made up of two distinct parts: the contribution of the applied air pressure (or pressure difference across the liner) and liner load. The fraction of air pressure transmitted by the liner to the sensor material covering can be thought of as a material characteristic of the liner, α, and is a function of the magnitude of air pressure, liner properties and the geometry of the liner bending around the teat end. As this applied load due to liner collapse reaches the material covering of the sensor, the magnitude of the force transmitted to the sensor is a function of the sensor covering, as the sensor covering also possesses a material characteristic we'll call β. These material characteristics are illustrated in Figure 7.

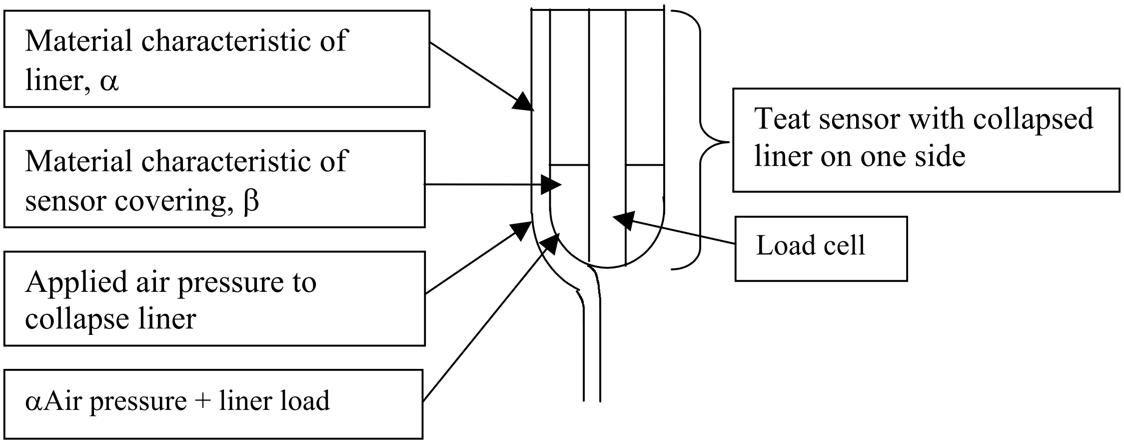

Figure 7 Diagram of hypothetical material characteristics and loads.

This relationship is also mathematically expressed in Equation 2:

$$\begin{aligned}\text{Total Sensor Response} &= \beta(\text{ Load}_{\text{due to applied air pressure}} + \text{Liner Load}_{\text{due to collapse}}) \\ &= \beta * \alpha * \text{Air Pressure} + \beta * \text{Liner Load}_{\text{due to collapse}}\end{aligned} \qquad (2)$$

where: α is a material constant of the liner

α=f(magnitude of air pressure, liner properties)

β is a material constant of the sensor covering

It is hypothesized here that α is a dynamic material constant that varies between zero and one. To illustrate how α can vary as a function of air pressure, consider a liner with a collapse point of 10 kPa, an applied pressure difference of 5 kPa will not collapse the liner; liner load due to collapse is zero. Furthermore, the liner wall absorbs the force of this applied pressure. Theoretically, load due to applied pressure is zero, making α in Equation (2) equal to zero. At the collapse point, α increases, thus transmitting a portion of the load through the liner to the sensor.

It must be stressed that Figure 6 shows the minimum liner loads, assuming that the force of the compressed air applied to the pulsation chamber was completely transmitted through the liner.

Given the hypothesis that $0 \leq \alpha \leq 1$, maximum liner load occurs when α is close to zero, minimum liner load occurs when $\alpha=1$. The results shown in Figures 6, 8 and 9 indicate minimum liner load, or assume that the entire amount of force from the applied air was transmitted through the liner and is thus subtracted from the liner load. Note the decrease in the load line at 10 kPa for each liner in Figure 6. This may be due to an incorrect assumption that $\alpha=1$ at an applied air pressure of 10 kPa. Since the collapse point of all liners tested was greater than 10 kPa, the total change in sensor response was similar between the measurements at 0 and 10 kPa, however, at 10 kPa the calculated liner load was the total response minus the contribution of air pressure. Though possibly incorrect, the assumption of $\alpha=1$ for all applied pressures was chosen for consistency in analysis. The exact value of α at each applied pressure is unknown.

MEASUREMENTS OF COMPRESSIVE LOAD OF LINERS: EFFECT OF LINER TENSION AND WALL THICKNESS

Sensor response to liner wall tension and thickness was tested with the excised teat tissue as a sensor covering. DeLatex and Conewango liners were tested at standard tension and wall thickness. The compressive load readings of these liners were compared to thin-walled DeLatex and when mounted in the shortened shell to reduce liner tension. The results are shown in Figure 8.

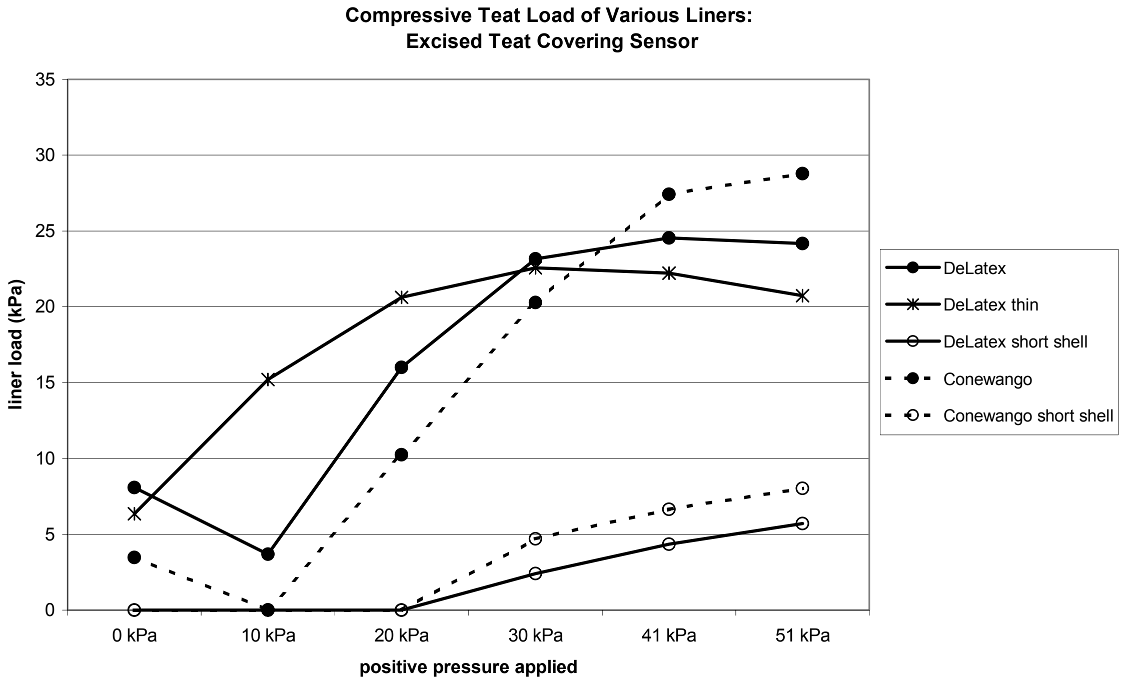

Figure 8. Effect of liner wall thickness and tension on liner load (kPa). Liners are denoted by liner style; normal, thin walled and low tensioned liners are denoted by marker style.

The measurement device responded as expected to varying liner tension and wall thickness. Similar to the findings of Mein and Williams (1984), Szlachta (1985), Mein et al. (1987), Hamman et al. (1994), Muthukumarappan et al. (1994) and Reinemann et al. (1994), the liners mounted in the shortened shell had a lower tension and therefore a lower compressive load. Also, the compressive load measurement (~22 kPa) for the thin liner at a pressure difference of 41 kPa is similar to that predicted by Muthukumarappan et al. (1994) for a liner with wall thickness of 2 mm.

It can also be readily seen from Figure 8 that the thin liner started to compress the teat sensor earlier than the standard liners. This result seems logical, since a thin liner requires less pressure difference to collapse. The lower compressive load, at pressure differences appropriate for milking, of thin liners was also reported by Hamman et al. (1994). Estimation of the compressive load by the Laplace formula (Equation 3) also shows that liner wall thickness is proportional to compressive load (Milnor 1974; Williams and Mein 1980, as cited in Williams et al. 1981)

$$P=\sigma t/r \tag{3}$$

where: P= pressure exerted by liner on the teat normal to the teat surface, kPa
σ= stress of collapsed liner, kPa
t= thickness of liner, mm
r= radius of curvature of liner around teat end, mm

MEASUREMENTS OF COMPRESSIVE LOAD OF LINERS: EFFECT OF INSERTION DEPTH OF DEVICE

Tests to determine the effect of insertion depth on compressive load were conducted with the excised teat tissue and the DeLatex liner. Penetration depths of 50 to 120 mm (2-4.7 in) were used at vacuum levels between 30 and 51 kPa (9 and 15 inHg). The results are shown in Figure 9.

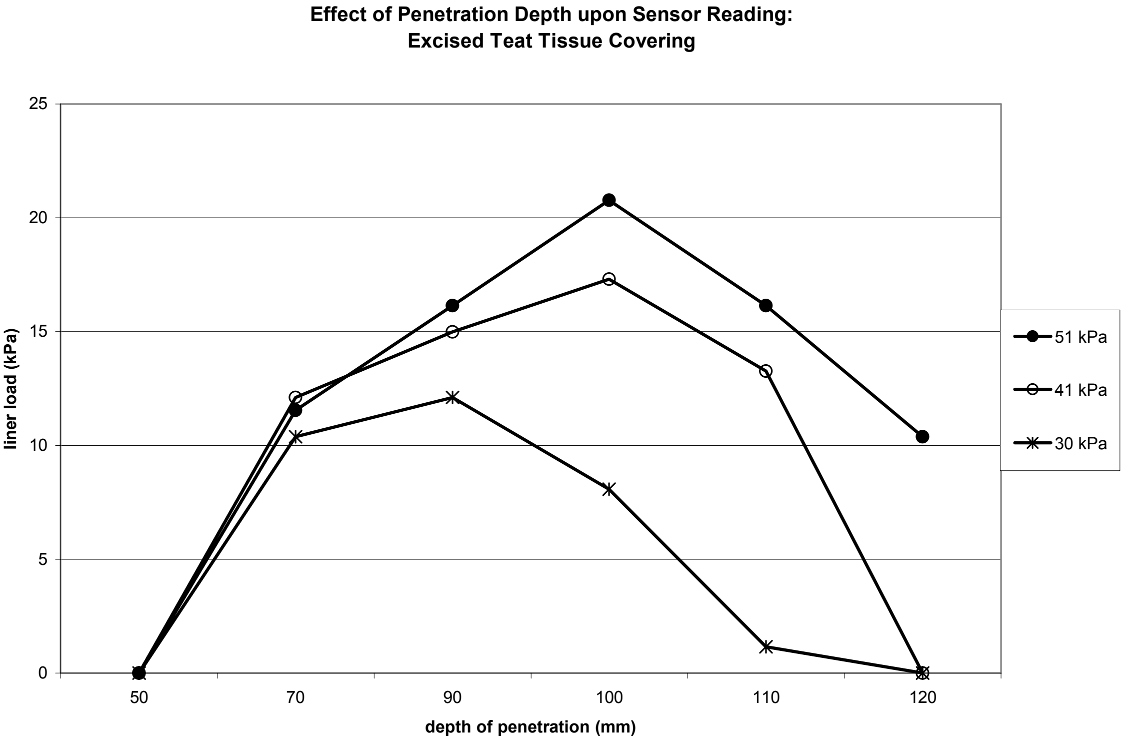

Figure 9. The relationship between compressive teat load and insertion depth was curvilinear.

The relationship between insertion depth and compressive teat load was curvilinear as expected and agrees with Caruolo (1983) who found this relationship for penetration depths of 20 to 97 mm. Note the increase in compressive load for pressure differences of 41 and 51 kPa at penetration depths up to 100 mm; Szlachta (1985) also found an increase in compressive load for pressure differences ranging from 40 to 53 kPa and penetration depths of 50 to 100 mm.

CONCLUSIONS

A gel-like material produced compressive teat load readings similar to teat tissue and is recommended for use as a sensor covering on the compressive teat load measurement device described in this study.

Compressive load was directly proportional to the longitudinal tension of the liner when mounted in its shell.

A curvilinear relationship was found between compressive teat load and penetration depth of the measurement device.

It is hypothesized that liner load in this work is composed of two distinct parts: the load of the applied air pressure to collapse the liner and the load applied by the liner as a result of bending around the teat end. It is also hypothesized that the load sensed by the sensor in this work is a function of a material characteristic of both the liner and the sensor covering material, but their value has yet to be determined.

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