Liner Compression applied to the bovine teat during the 'rest-phase' of the pulsation cycle: everything you always wanted to know – and much more ..!

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Abstract
This purpose of this paper is to clarify the concept of liner compression and to show the practical importance of understanding and controlling its effects. The degree of compression applied to the teat by the teatcup liner in the d-phase of pulsation has a marked influence on teat condition, cow comfort and peak milk flow-rate. The influence of liner compression on these three characteristics is at least as great as the effects of pulsator ratio, pulsation rate, and the rates of change in air pressure in the teatcup pulsation chamber.

If a liner had a wall thickness as thin as a balloon, or a condom, such a liner would exert almost no compression, above atmospheric pressure, on the teat when the teatcup pulsation chamber is at atmospheric pressure during the d-phase of pulsation. Because the wall thickness of successful commercial liners (typically 2-3.5 mm) is much thicker than that of a balloon or a condom, all commercial liners compress the teat to varying degrees when they close in each pulsation cycle.

Liner Compression (LC) is defined here as the mean compressive pressure (expressed in kPa or inHg above atmospheric pressure) which is applied to the inner tissues of the teat apex by the liner during the d-phase of pulsation.

Over-pressure (OP) is defined as the mean compressive pressure, <u>above that required to stop milk flowing from the teat</u>, which is applied to the inner tissues of the teat apex by the liner during the d-phase. Thus, OP is a major component of LC.

A useful practical advantage of OP is that, at present, OP is simpler than LC to measure or estimate during a milking-time test. OP can be estimated by careful measurement of the vacuum level in the teatcup pulsation chamber (PCV) at which milk starts or stops flowing from a teat. This point, which is defined as SMF (meaning Start or Stop Milk Flow) occurs when the distending force acting on the teat (due to liner vacuum) is counter-balanced by sufficient compressive force applied by the liner to close the teat canal. Because OP is affected by teat size and shape of the teat apex, SMF should be measured on one teat of about 10 different cows to get a reliable average value for any given liner.

The average OP applied by different commercial liners to a teat of 'average' size and shape varies from <5 to >20 kPa (<1.5 to >6 inHg). The main factors producing this remarkably wide variation are: wall thickness of the liner barrel; hardness of the liner material; mounting tension of the liner in its shell; and cross-sectional shape of the liner barrel.

Liner OP values within the range 8-12 kPa appear to achieve the main purposes of pulsation and to maintain good teat condition and cow comfort. OP values < 8 kPa may be too low to fully relieve teat wall congestion induced by the milking vacuum during the b-phase of pulsation. Peak milking rate continues to increase up to liner OP values of 14 kPa. However, the proportion of cows with poorer teat-end condition (hyperkeratosis) appears to be greater at OP values of 14 kPa or more.

An important practical implication of these results is that the Over-Pressure applied by some liners is too low to obtain the full benefits of faster milking when vacuum level is raised. At the other end of the commercial range, liner OP may become too high when vacuum level is raised, thereby leading to poorer teat-end condition.

Introduction

For the past 100 years, effective pulsation has been described mainly in terms of a vacuum recording of the cyclic changes in air pressure in the teatcup pulsation chamber (PC). From about 1967, pulsation was defined more specifically as 'cyclic opening and closing of a teatcup liner'. At about the same time, the term 'pulsation ratio' was used in a few scientific papers to define the proportion of time - within each pulsation cycle - that the liner was more than half open. In the USA, this concept was adapted to define the 'milk:rest ratio' for a given liner based on its 'touch point'. A milk:rest ratio of 60:40, for example, implies a 'milking phase' of 60% of each pulsation cycle followed by a 'massage phase' of 40%. The two phases are assumed to start and stop at the point where the opposing liner walls first touch each other when measured with no teat in the liner.

In the last 20 years, two further proposals have been made to define effective pulsation in terms of:

- changes in thickness of the teat-end measured just before and immediately after milking (Hamann & Mein, 1996);
- cyclic over-pressure (or compressive load) applied by the closed liner to the teat in each pulsation cycle (Mein et al., 1987; Mein et al., 2003, Ronningen, 2003).

To date, however, neither of these proposals has made much impression on the commercial world of machine milking. To the best of our knowledge, only one udder health adviser has included liner compression as a routine measurement for trouble-shooting on farms in the past 10 years (Luismi, www.servettalavera.es). The commercial world continues to concentrate on excessively detailed analysis and reporting of vacuum changes recorded in the teatcup PC. This is not too surprising - most of us prefer to measure the things which are easy to measure, rather than those things that may be more important but are more difficult to measure. Nevertheless, the cyclic changes in vacuum in the teatcup pulsation chamber are less than half of the story about effective pulsation. The two other key factors are:

- liner vacuum during the d-phase of pulsation (because this affects the pressure difference applied across the liner wall);
- physical properties of the liner (eg, its composition, geometry, tension and age).

These factors have great influence on milking speed and teat condition because all forces generated by the pressure difference (PD) across the liner walls are transmitted to the teat via the liner itself.

Some relevant definitions

'Pulsation'
Pulsation is defined in ISO (2007) as liner wall movement, ie, cyclic opening and closing of the liner barrel. In the past 20 years, a few scientists (eg, O'Callaghan, 1997; Schuiling, 2003; Spencer, 2003) have made systematic measurements of the rates and times of liner wall movement. An interesting insight from studies such as Spencer (2003) is that the rate of liner movement is remarkably slow. Typically, the rate of liner opening is about 40 times slower than the relaxed walking speed of a healthy adult and the rate of liner closing is 12 to 14 times slower!

'Touch Point' (also known as *'collapse force' or 'liner offset' or 'kiss point'*)
Touch Point, measured without a teat in the liner, is usually defined as the pressure difference required to collapse the liner to the point where the opposing walls of the liner barrel first touch each other.

'*Residual vacuum available for massage' (RVM)*
This value is obtained by subtracting the vacuum required to collapse the liner (ie, the liner 'Touch Point') from the average claw vacuum. For a given claw vacuum, therefore, RVM is assumed to decline in direct proportion to any increase in the vacuum required to collapse the liner. This basic concept is enshrined in the calculation of an assumed milk:rest ratio (eg, see Appleman *et al.*, 1967) which is based on the points at which milk is assumed to start and stop flowing from a teat within a pulsation cycle.

'Liner Compression' (LC)
LC is the mean compressive pressure (expressed in kPa or inHg above atmospheric pressure) applied to the inner tissues of the teat apex by the liner during the d-phase of pulsation. Descriptions and measurement methods need clarification to distinguish between Liner Compression and liner OP. Also described as '*Compressive pressure'* (Ronningen, 2003).

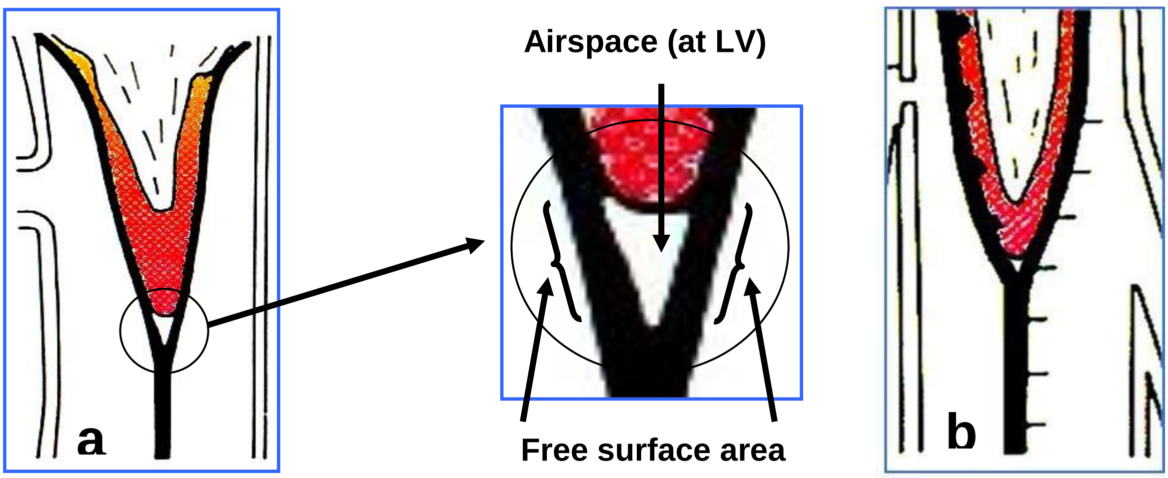
'Over-pressure' (OP)
Liner OP is the mean compressive pressure, above that required to just stop milk flow from the teat, which is applied to the inner tissues of the teat apex by the liner during the d-phase (Mein et al., 2003). Liner OP was described, initially, as *'Compressive Load*' and expressed in kPa (Mein et al., 1987) because it seemed simpler to measure or estimate it as a pressure. Engineering purists would argue, correctly, that the concept of Compressive Load should have been expressed as a force (N) rather than as a pressure (kPa) because the term 'load' is used in engineering to mean the force exerted on a surface or body. Also described as 'Liner Compression' (Reinemann et al., 2008; Bade et al., in press).

'True milk:rest ratio'
The true milk:rest ratio is an expression for the proportion of time - within each pulsation cycle - that milk flows from a teat, relative to the proportion of time that milk flow is stopped by compressive force exerted by the liner. It is based on measurement of the average vacuum level in the teatcup pulsation chamber (PCV) at which milk starts or stops flowing from a teat (defined as *'SMF'* by Bade et al., in press). This is the point at which the distending force acting on the teat (due to liner vacuum) is counter-balanced by sufficient force applied by the liner to compress and close the teat canal.

Generation of Liner Compression (LC)

Directly beneath the compressed teat in a closed liner, there is always a small airspace which is connected to the source of milking vacuum by channels formed by incomplete folding of the edges of the collapsed liner. This airspace (see enlargement in **Fig 1**) is the key to understanding both the source and the degree of liner compression. The pressure difference, acting across the surface area of the liner walls that surround this airspace, is the source of the force that compresses and massages the teat during the d-phase of pulsation. The greater the pressure difference, the greater the total compressive force. Typically, the total compressive force is reduced when liner vacuum falls during the peak flow-rate period of milking. The free surface area increases with higher liner tension which, therefore, produces greater compressive force (Fig 6 in Muthukumarappan et al., 1994)

Fig 1. Tracings of two old radiographs (from Mein, 1992) which show: a) a teat in a closed, highly-tensioned extruded rubber liner; b) a different teat in a thicker-walled, low-tensioned, soft silicone liner. If you think the teat apex shown in Fig 1a seems to be more squashed and flattened than the teat apex in Fig 1b, you would be quite correct. In fact, the LC applied by these two liners to the teat apex is about 5 times higher in Fig 1a than in Fig 1b (see **Appendix 1** for details of such calculations).

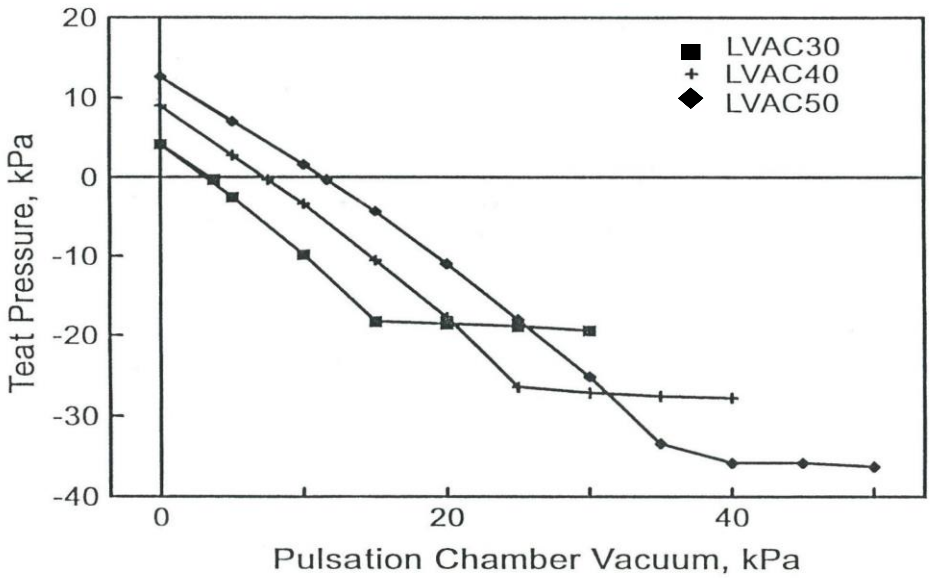


Not all of the total compressive force that is generated is available to compress the teat, however. The difference between the total and the available compressive force is often quite large, as discussed later in relation to Fig 3. Most of the available compressive force (ie, the 'compressive load') is applied to the distal end of the teat over an area of 400–600 mm^2 (0.6–1 in^2). Half of this total area is located on either side of the plane of liner collapse. The average pressure (the LC) can be estimated by dividing the available compressive force by this area (see Appendix 1 for details of such calculations).

Factors affecting LC

Liner Compression (LC) available to compress the teat during the d-phase is increased progressively by greater PD acting across the liner walls (**Fig 2)**. The absolute values shown in Fig 2 need to be interpreted with caution because they were obtained with an artificial teat. Nevertheless, the general relationships are instructive and they are consistent with field experience.

Fig 2. Effect of progressive changes in Pulsation Chamber Vacuum (PCV) on pressure within an artificial teat sensor at three steady levels of Liner Vacuum (LVac) (from Muthukumarappan et al., 1993, Fig 5). See Muthukumarappan et al. (1994) for details of sensor and measurement method.



The point at the lower right-hand end of each curve shown in Fig 2 is where LVac = PCV. Starting from this point and moving to the left, the near-horizontal section of each curve confirms that almost no pressure is applied to a teat until the pressure difference is high enough to cause the barrel of the liner to buckle (15 kPa for the liner used in this particular study). Once the buckling point is reached, further incremental reduction in PCV (ie, increase in air pressure in the PC) induces a progressive but non-linear increase in pressure within the teat sensor. The point at the upper left end of each curve shows the final pressure within the teat sensor for a pressure difference (PD) of 30, 40 or 50 kPa across the liner wall. Note that these differences of 10 kPa in the final PD for the three curves produced a difference in maximum pressure, within the artificial teat, of about 5 kPa between the 30 & 40 kPa curves and only about 3.5 kPa between the 40 & 50 kPa curves. The slight non-linearity in each curve, and also the relatively small differences in final maximum pressure within the artificial sensor, is consistent with losses in RVM due to components 1 and 2 which are illustrated in **Fig 3**.

Teat length, diameter and shape also affect LC. For example, teats may experience a lower LC if they are unusually short (because the liner cannot apply much compression when it does not have to bend so far to collapse beneath the teat). Similarly, unusually long teats may experience little or no LC if they penetrate too deeply into the liner and thereby prevent the liner from closing fully beneath the teat-end. Conversely, wide flat-bottomed teats may experience a relatively high LC because the liner has to bend further and also because the free surface area beneath the teat is increased. For the same reason, most teats experience higher LC in the low flow-rate period of milking because the teat wall rapidly becomes more congested after the end of the peak flow-rate period (see **Appendix 1**).

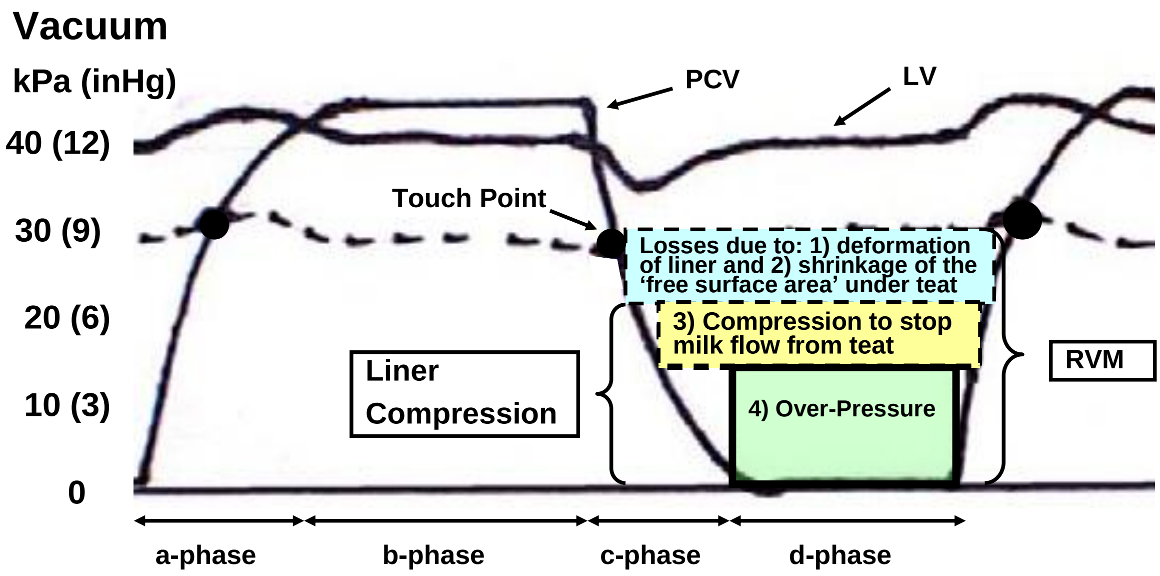
Slender pointed teats often experience a more subtle effect leading to increased frequency or severity of teat-end hyperkeratosis. Although the compressive load generated on a slender pointed teat generally is less than that for a wide, flat teat-end (because the liner has to bend further around a wide, flat teat), the load is spread over a smaller area of teat tissue of a pointed teat-end. The resultant load concentration increases the likelihood of teat-end damage. As a simple analogy, think of a woman in stiletto heels walking across a polished wooden floor. Although she might weigh 60 kg or less, the woman is more likely to damage the floor compared with a 90 kg man who is wearing flat shoes. Why? Although the woman produces 50% less total load on the surface of the floor, her heels exert a much greater pressure because the load is concentrated over a much smaller area.

Some indicative effects of teat or liner characteristics on Liner Compression are given in Table 1.

Table 1. Likely changes in LC associated with changes in resistance of the liner to bending:
a) around the teat apex (in both vertical and horizontal planes);
b) along the folded edges of the plane(s) of collapse of the liner barrel.

Factor	**Main effect**	**Likely net change in LC**
Teat size and shape		
Bigger teat apex	Liner has to bend further to close around the apex	Higher
More congested teat	Liner has to bend further to close around the apex	Higher
Very short teat	Less bending of liner around the apex	Lower
Very long teat	Very long teats may prevent the liner from collapsing around the teat apex	Much lower
Machine settings		
Higher claw vacuum	Greater PD across wall of collapsed liner	Higher
Liner characteristics		
Higher mounting tension	Larger airspace beneath teat apex, higher resistance to bending around the apex	Higher
Increase in wall thickness, from 0.1 to ~2mm	Greater resistance to bending around apex. Greater resistance to bending along folded edges	Higher
Increase in wall thickness, from ~2 to 3.5mm	Greater resistance to bending around apex. Greater resistance to bending along folded edges	Lower
Increase in hardness, from ~35 to ~ 50 ShoreA	Greater resistance to bending around apex. Greater resistance to bending along folded edges	Higher
Increase in hardness, from ~50 to ~ 60? ShoreA	Greater resistance to bending around apex. Greater resistance to bending along folded edges	Lower
Old liner nearing the end of its designed working life	Lower LC due to loss of mounting tension Higher LC due to small changes in barrel shape (more oval shaped) and less resistance to bending along the folded edges of the plane of collapse	? Depends on the balance of these opposing effects
Square cross-section	Need reliable measurements	?
Triangular cross section	Need reliable measurements	?

Fig 3. Relationships between Liner Vacuum (LV), Touch Point (TP), Residual Vacuum available for Massage (RVM), Pulsation Chamber Vacuum (PCV), PCV when milk starts flowing from the teat (SMF), Liner Compression (LC) and Over-Pressure (OP).



The RVM is obtained by subtracting the pressure difference required to collapse the liner (ie, the liner 'Touch Point') from the mean claw vacuum (which is, essentially, LV in Fig 3), ie, RVM = [LV – TP]

Starting from the beginning of the c-phase of a pulsation cycle:

- the liner applies no compression to the teat until the pressure difference across the liner wall is sufficient to initiate buckling of the liner (see **Fig 2**);
- most conventional liners apply very little compression until the pressure difference rises (PCV falls) sufficiently to reach TP for a given liner;
- after TP is achieved, the compression applied to the teat increases progressively as the pressure difference continues to rise, reaching its maximum level when the PC is at atmospheric pressure during the d-phase of pulsation.

There are some exceptions to the general statement that most conventional liners apply very little compression to the teat until TP is reached. For example, the high-tensioned liner shown in Fig 1a applied sufficient compression to the teat apex to stop milk flow – completely **-** before TP (see Fig 4.4 in Mein, 1992 for further details). Despite these exceptions, it is a convenient simplification to consider TP as the starting point for Liner Compression (ie, LC = 0 kPa above atmospheric pressure). From this point onwards, the RVM is dissipated or utilised as follows.

1. Some of the RVM is dissipated (lost) due to: progressive deformation of the liner material as it stretches and bends around the teat; and to resistance to bending along the folded edges of the plane(s) of liner collapse.
    - The extent of the losses due to internal deformation depends on the material properties of the liner and its temperature. [Note: Such losses in a liner made of the type of rubber used in a child's bouncy 'super ball', for example, would be relatively low compared with the loss due to internal deformation when a squash ball hits and rebounds from a hard surface (77-88% loss in kinetic energy, depending on the temperature of the squash ball)].
    - Losses due to resistance to bending increase with increasing wall thickness over the range of about 2mm to 3.5mm for typical, commercially-available liners (Mein et al., 2003). Such losses, together with the effects of hardness of liner material (Fig 8 in Muthukumarappan et al., 1994), can utilise most of the available RVM in some cases.

2. Some of the RVM is ‘lost’ as the airspace beneath the teat becomes progressively smaller because the opposing walls of the liner meet and support each other beneath the teat.
3. Some is used to start alleviating congestion and to compress the teat to the point where milk flow stops or starts (ie, the SMF point).
4. The remainder is utilised in further compression of the teat apex to alleviate congestion and, perhaps, oedema induced by the liner vacuum during the b-phase.

These relationships are illustrated in **Fig 3**. The sum of components 3 and 4 is the LC. The line of demarcation between components 3 and 4 is determined by the PCV at which milk starts or stops flowing from a teat (described by Bade et al. as the ‘SMF’). Component 4, the liner OP, is the simplest and easiest component to measure in the field at present.

Essentially, liner OP is equal to the incremental increase in air pressure in the teatcup PC (ie, the decrease in PCV) starting from the point where milk just stops flowing and ending when PCV is at atmospheric pressure. If milk flow starts and stops at a PCV of 12 kPa, for example, then the mean OP will be ~ 12 kPa during the d-phase. This simple approximation can be inferred from the curves shown in Fig 2. This approximation provides a reasonable estimate for practical purposes because the incremental losses due to components 1 and 2, in the list above, are likely to be small once the SMF point has been reached.

The average OP applied by different commercial liners to a teat of ‘average’ size and shape varies from <5 to >20 kPa (<1.5 to >6 inHg). As indicated in Table 1, the main factors producing this remarkably wide variation are: wall thickness of the liner barrel (ranging from about 2 – 3.5mm); hardness of the liner material (typically about 35 ShA for natural rubber, 40-45 ShA for soft silicone liners, 48-55 ShA for nitrile rubber liners); mounting tension of the liner in its shell (ranging from about 40 – 100 N); and cross-sectional shape of the liner barrel (circular, oval, triangular or square).

Liner Compression (LC) is NOT the same as point pressures measured at the teat-liner interface

LC is a measure or indication of the average pressure experienced by the inner tissues of the compressed teat apex. Values for LC should not be confused with the point pressures generated at the interface between the liner surface and the teat skin. According to van der Tol (pers. comm. to G. Mein, Oct 2008), maximum point pressures at the interface - where the inner surfaces of a liner and the external surface of a teat are pressed against each other and are subjected to local shear forces - are much higher than the average values which are transmitted to the soft internal tissues of the teat wall.

The skin of the teat acts like a tough string bag to prevent undue stretching of the inner tissues. The inner tissues of the teat wall surrounding the teat sinus <u>cannot</u> experience any pressure greater than intra-mammary pressure unless the opposing walls of the teat sinus are occluded to the extent that they press against each other. That is why the compressive force applied by most liners acts mainly (or, perhaps, only?) over the distal end of the teat (~15 mm). For highly-tensioned liners, the compressive force can be applied over a 20-25mm length of the distal end, including part of the teat sinus.

Effect of liner OP on peak milk flow-rate

The remarkable effects of liner compression on the instantaneous rate of milk flow, within single pulsation cycles, were first shown by Williams et al. (1981). Figs 4 and 5 are extracted from that paper for convenience of readers.

The traces reproduced in **Fig 4** were recorded during the peak flow-rate period of milking. The degree of compression was varied by controlling the PCV at different levels during the d-phase while maintaining a constant liner vacuum of 50 kPa. The duration of liner closure was 500 ms in all cases and the liner open time was 1500 ms. The relatively slow pulsation rate (30 c/min) was selected so that time-dependent changes in the flow-rate profile could be seen more clearly. The control treatment was a pressure difference (PD) of 50 kPa during the d-phase.

A striking feature of these results is the size and rapidity of the flow-rate change in response to a step change in PD across the liner wall – changes that occurred within the time-period of a single d-phase! The characteristic flow-rate profile for the control treatment shows:

- the typical immediate rise in flow-rate to its maximum value as soon as the liner opens in each cycle;
- a small fall in milk flow-rate during the first 500 ms of liner open time; followed by a much steeper fall to a lower equilibrium level over the next 1000 ms.

Reducing the PD from the control value of 50 kPa (atmospheric pressure in the PC) in steps of 10 kPa progressively reduced the amount of milk obtained per cycle. Below a PD of about 20 kPa, milk flowed continuously from this teat because the degree of compression was insufficient to flatten and close the teat canal. Increasing the PD above 50 kPa induced an immediate increase in total yield of milk obtained per pulsation cycle.

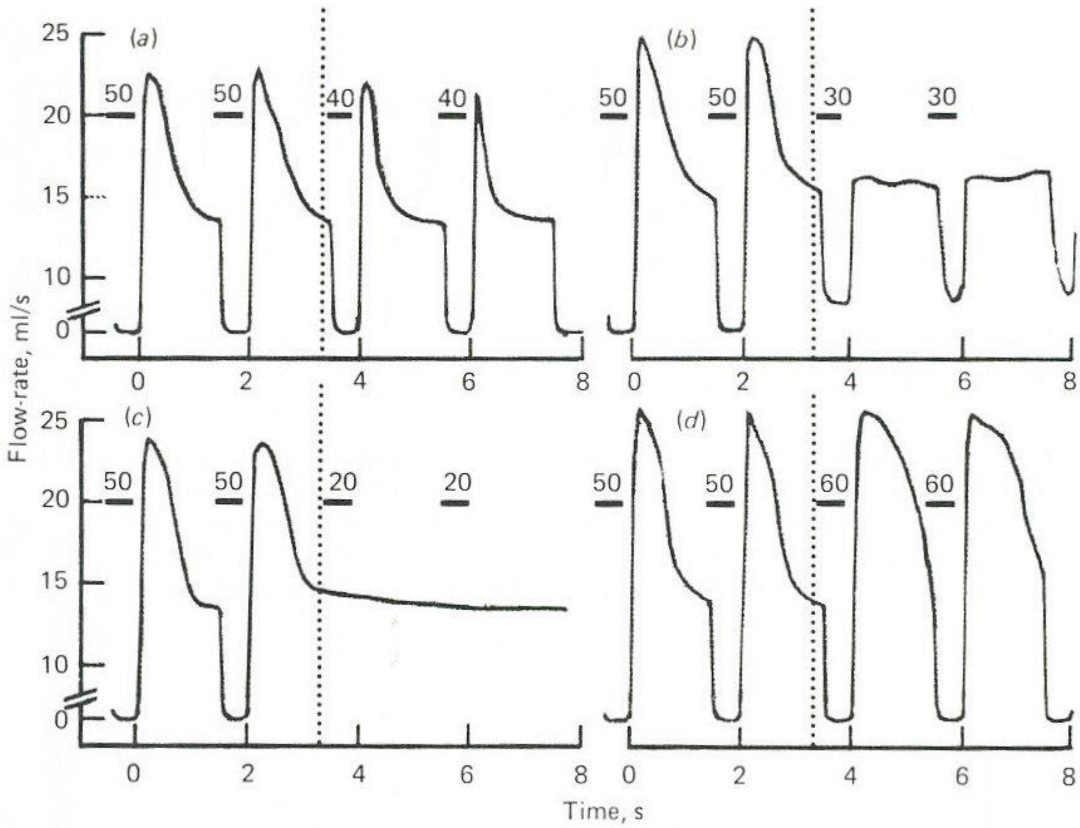
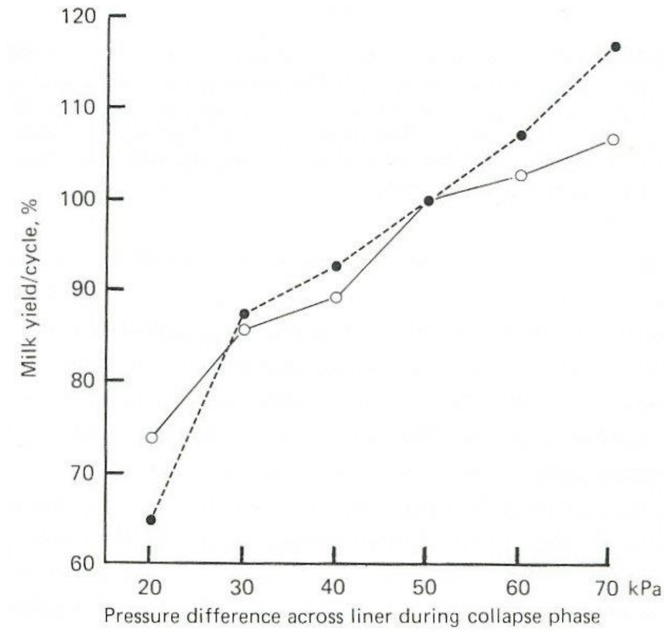


Figure 4. Effect of varying the degree of compression applied by a liner to the teat apex during the d-phase on the milk flow-rate profile in the following b-phase of individual pulsation cycles (from Williams et al., 1981). Numbers on these traces indicate the pressure difference (PD in kPa) across the liner wall during the d-phase of pulsation. Dotted lines represent the instant when the PD was varied from the control level of 50 kPa to: (a) 40 kPa; (b) 30 kPa); (c) 20 kPa; (d) 60 kPa.

Fig 5. Percentage change in milk yield per cycle plotted against the pressure difference (PD) across the liner during the d-phase for two different liners (from Williams et al., 1981).

Milk yield per cycle is expressed as a percentage of the mean yield obtained for a PD of 50 kPa. and a relatively slow pulsation rate of 30 c/min.

Results at more typical pulsation rates of 55 to 65 c/min would not be as dramatic as those shown here. Why not? Because the main effect of a faster pulsation rate is to avoid the drop in flow-rate, illustrated in Fig 4, which occurs after the first 500 ms of the liner open phase.



Now, we can fast-forward from 1981 to 2008. The profound effects of liner compression on peak milk flow-rate have been elucidated in a series of new studies summarized by Reinemann et al. (2008). In the first experiment, changes in peak milk flow-rate (PFR) were used as an indicator of the degree of machine-induced congestion of teat tissues that occurs during the liner-open phase of a pulsation cycle. This study broke new ground in that the three main variables affecting PFR were controlled independently. The three variables were: claw vacuum (range 42 to 53 kPa); duration of b-phase of pulsation (range 220 to 800 ms); and liner OP (range 8 to 14 kPa).

A remarkable feature of this new study was that raising the milking vacuum produced very little increase in PFR when liner OP was maintained at a pre-set, low value (8 or 11 kPa). Under these closely controlled test conditions:

- PFR actually <u>fell</u> from 4.2 to 4.1 kg/min when claw vacuum was raised from 40 to 46 kPa (ie, by 6 kPa) for a constant liner OP of 8 kPa and b-phase of 800 ms.
- PFR was 4.4 kg/min at a claw vacuum of 46 kPa for a constant liner OP of 11 kPa and b-phase of 800 ms.
- PFR was 4.8 kg/min at a claw vacuum of 46 kPa for a constant liner OP of 14 kPa and b-phase of 800 ms.

Thus, PFR increased by 17% (from 4.1 to 4.8 kg/min) when the liner OP was raised from 8 to 14 kPa. A key conclusion from this study is that liner OP is sometimes too low to obtain the full benefit of faster milking when claw vacuum is raised. Peak milk flow-rate continued to increase up to a liner OP of 14 kPa - the highest OP tested by Reinemann et al (2008). However, there were indications that poorer teat-end condition was associated with liner OP as high as 14 kPa. This critical aspect of teat health is discussed in the following section.

Effect of liner OP on teat-end condition

A target range of 8-12 kPa for liner OP was proposed by Mein et al. (1987) who suggested that OP values above about 12 kPa may be unnecessary from a physiological viewpoint. Subsequently, three experienced udder health consultants in the USA were asked, independently, to rank a short list of commonly-used liners in terms of their observed effects on teat-end roughness in commercial herds. Their responses covered a total of 7 of the 18 liners for which liner OP data were available at that time. Preliminary results suggested that liner OP values above 12-13 kPa (about 3.5-4 inHg) may be undesirable for liners that are used for milking high-producing herds 3 or more times per day in the USA (Mein et al., 2003).

Field studies summarized by Reinemann et al. (2008) confirmed that increasing liner compression increased the development of teat-end hyperkeratosis (refs Bade? Zucali?)

Field results from Spain suggested that teat-end condition (at a herd level) remained good, in herds milked twice per day, over the range 8.5 -14.5 kPa for mean OP (Perez et al., 2008).

An udder health specialist from Spain (Luismi, pers. comm., Oct 2008), measures OP routinely in any herd with bad teat condition (that is, when >20 % of all cows have teat-ends classed as Rough plus Very Rough). If the OP is <8 or >14, Luismi recommends adjustment of claw vacuum and/or characteristics of the liner.

'Take-home' messages

The degree of liner compression applied to cows' teats has such great influence on milking speed and teat condition simply because all of the forces generated by the milking machine are transmitted to the teat via the liner itself.

Liner OP values within the range 8-12 kPa appear to achieve the main purposes of pulsation and to maintain good teat condition and cow comfort. OP values < 8 kPa may be too low to fully relieve teat wall congestion induced by the milking vacuum during the b-phase of pulsation. Although peak milking rate continues to increase up to liner OP values of 14 kPa, the proportion of cows with poorer teat-end condition (hyperkeratosis) appears to be greater at 14 kPa or higher levels of teat compression.

High liner OP also affects cow comfort. To imagine how a high cyclic pressure might affect a cow's comfort level when applied to her teats for 5-10 min, two or three times every day, think how your feet would feel if you were forced to march for 5-10 min, two or three times every day, in shoes that are too tight.

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(refs Bade? Zucali?)

Appendix 1. Generation of Liner Compression (LC)

Extract from Mein et al., 1987.

The total compressive force that is generated across the liner walls beneath the teat is spread around the boundaries of the free surface area (wyxz in Fig 1.1a and c) as described below.

- Part of the total load is supported by the stiffness of the folded edges of the liner along the outer margins of its plane of collapse. The support provided by resistance to further bending of these folded edges is similar in concept to the support that would be provided by small springs placed at each side of the flattened teat-end to resist any further collapsing of the liner walls.
- Part of the total load is supported by the opposing walls of the liner where they meet along the lower margin of the free surface area (yz).
- The remainder of the total load is supported along the upper margin of the free surface area (wx). The shaded area of the flattened teat apex, shown in Fig 1.1a and c, takes most of this 'available' compressive load.

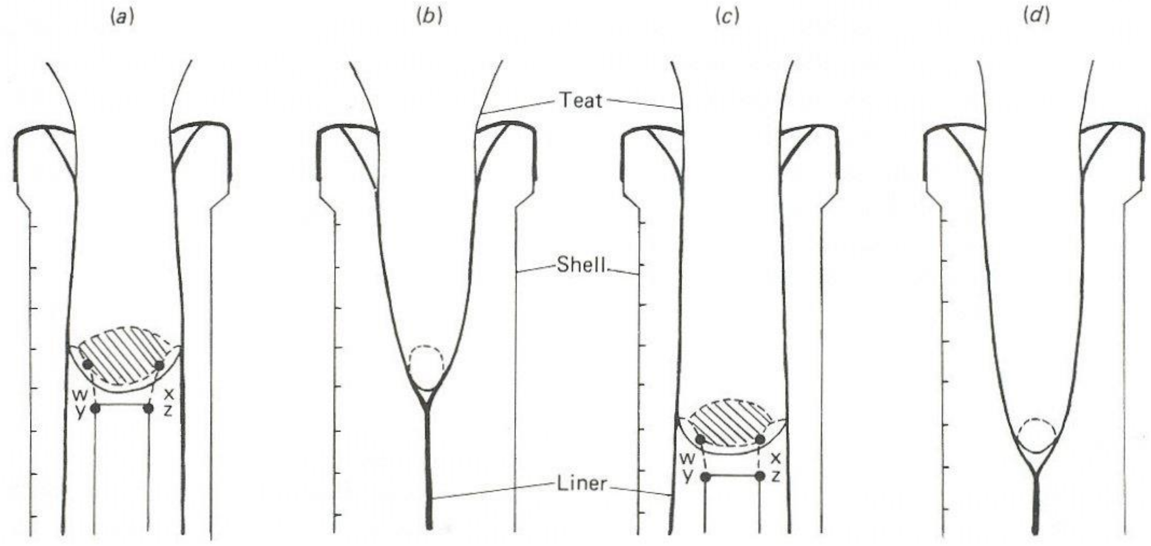

Fig. 1.1 Tracings from photographs of a teat in a transparent teatcup during the d-phase of pulsation (Fig 4 from Mein et al., 1987). This sequence shows the same teat during the peak flow-rate period (a and b) and low flow-rate period (c and d) of milking. A mirror mounted vertically at about 45^{o} on the side of the transparent teatcup provided simultaneous views of the teat and liner both perpendicular (a and c) and parallel (b and d) to the plane of liner collapse. The transparent shell is marked at 10mm intervals. Shaded area in Figs 1.1a and c represent the area which is taking most of the compressive load applied by to the teat by the closed liner. The area bounded by points marked w, x, y and z represents the 'free surface area' (see text). The opposing walls of the liner are in contact over the area directly below the horizontal line yz. Dashed lines in Figs 1.1b and d show a side view of the margin of contact between the teat and liner.

Each unit length of the supporting boundaries distributes an equal share of the total load. The load taken by the teat apex is therefore proportional to the length of the upper margin of contact (wx) divided by the sum of the lengths of all four boundaries of the airspace in profile (wx + xz + yz + wy).

The collapsed liner has two free surface areas, one on each side of the plane of liner collapse. Because they are roughly symmetrical, the total compressive force acting on the teat apex is twice the product of the pressure difference (PD), the boundary ratio (BR) and the free surface area (FA). In Fig 1.1a, BR = 0.39, FA = 1 x 10^{-4} m^2 and PD = 50 kPa. Total load exerted on the teat apex is therefore 3.9 N.

Most of this load is taken over an area of the teat apex of about 520mm^2 (260mm^2 on either side of the plane of collapse). The mean pressure on the teat apex – ie, the Liner Compression – is therefore about 7.4 kPa.

Similar calculations for Fig 1.1c indicate that the mean Liner Compression had increased to about 9.2 kPa during the low flow-rate period of milking for this particular teat and liner combination. More details of these calculations of boundary ratio (BR), compressive force and mean pressure applied to the teat apex are given in Mein et al. (1987).