

EFFECTS OF MILKING ON TEAT-END HYPERKERATOSIS: 1. MECHANICAL FORCES APPLIED BY THE TEATCUP LINER AND RESPONSES OF THE TEAT

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Teat-end hyperkeratosis is a thickening of the skin that lines the teat canal and surrounds the external teat orifice. The condition is variously described as teat rings, teat flowers, teat erosion, callus formation, callosity, cornification or teat-end roughness. Histological examination of teat sections confirms that teat-end hyperkeratosis results from a localised hyperplasia of the *Stratum corneum* (Neijenhuis *et al.* 2001) or *Stratum corneum* and *Stratum granulosum* skin layers (Hamann *et al.* 1994). Therefore, descriptions such as "teat inversion", "teat eversion" or "prolapsed teats" are incorrect.

Hyperkeratosis means "excessive keratin growth". It is a normal physiological response to the forces applied to the teat skin during milking, either by a milking machine, a hand-milker or a calf. The onset and severity of hyperkeratosis is profoundly influenced by the over-riding effects of climate, seasonal and environmental conditions, milking management, herd milk production level and genetics of individual cows (Ohnstad *et al.* 2003). Reports of teat-end hyperkeratosis problems are far more prevalent in high-producing herds, for example, and especially during the colder periods of the year. Despite the fact that the same cows are milked with the same equipment by the same operators throughout the year, milking machines often get the blame for poorer teat condition during the winter months. The purpose of this paper is to explain some of the mysteries of the main machine effects on cows' teats and the hyperkeratotic response of teat.

Teat-end hyperkeratosis is related to the type of mechanical milking conditions applied to the teat and to the length of time per day that teatcups are attached to teats. Hyperkeratosis is absent or markedly reduced in cows milked without pulsation (Tolle and Hamann, 1978; Woolford and Phillips, 1978). Hyperkeratosis increases with increasing pressure applied to teat-ends by teatcup liners and by the use of compressed air, applied during the D-phase of pulsation in some pulsation systems, to massage and stimulate teats more intensively (Bothur and Wehowsky, 1985; Hamann *et al.* 1994). Hyperkeratosis is reduced by adjusting threshold settings of automatic cluster removers to shorten average milking times per cow (Rasmussen, 1993).

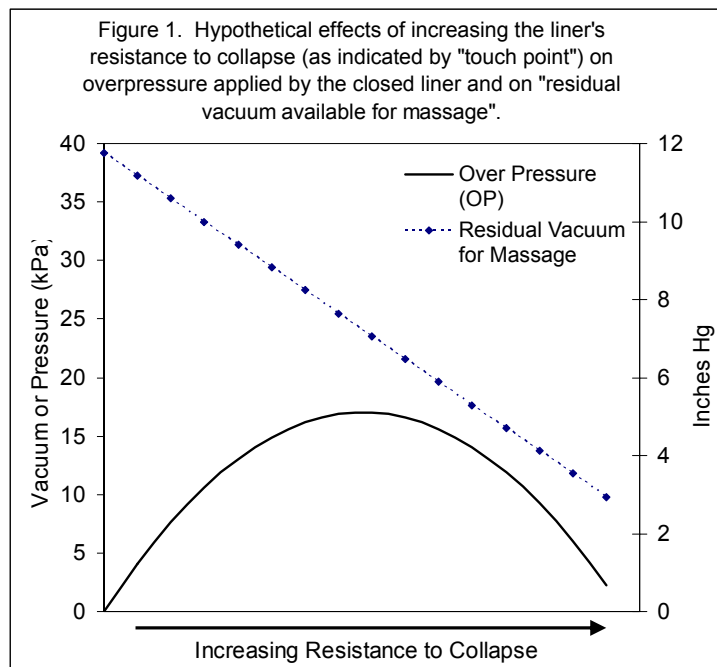
These types of experimental results and field observations lead to a concept of the amount of "over-pressure" (also known as the "compressive load") that is applied to a teat by the closing or closed liner. By this we mean the average pressure, above atmospheric pressure, applied to a teat by the liner as it bends around the end of the teat within each pulsation cycle.

The collapsed liner applies little or no pressure to the **teat barrel** and does not close the teat sinus at any stage of milking. This point can be demonstrated by inserting the finger of a rubber glove, as an artificial teat, into a transparent teatcup. Closure of the liner during the C- and D-phases of pulsation

does not flatten the glove finger. Neither the glove finger nor the teat barrel is squashed flat because their inner surfaces are at or above the pressure in the pulsation chamber (ie. atmospheric pressure). The **tip** of the glove finger becomes flattened and wedge-shaped, however. The end of a cow's teat is compressed in the same way as the glove fingertip by the pressure exerted on the teat-end by the collapsed liner. This local pressure results from the use of a relatively stiff-walled liner, which is mounted under tension and forced to bend around the end of the teat. **If the liner walls were infinitely thin then no additional pressure, above the pressure of the air in the pulsation chamber, would be applied to the teat-end.**

It follows that very soft thin-walled rubber liners, which require only a small pressure difference for collapse, apply relatively little "over-pressure" to the teat. Over-pressure increases progressively with increasing wall thickness (and/or with increasing rubber hardness) up to some maximum level. Eventually, however, the increase in applied load must decline. Clearly, a liner that is too thick to be collapsed by the pressure differences applied in conventional teatcups cannot apply any over-pressure to the teat. This concept is illustrated in Figure 1.

The American concept of "residual vacuum available for massage" is also illustrated in Fig 1. This basic concept (eg. see Appleman *et al*, 1967) is enshrined in the modern-day calculation of milk: rest ratio. The points at which milk is assumed to start and stop flowing from a teat within a pulsation cycle ratio are calculated by subtracting the vacuum required to collapse the liner (known as the liner "touch point", "offset" or "kiss point"), from the average claw vacuum. For a given claw vacuum, therefore, the "residual vacuum available for massage" is assumed to decline in direct proportion to any increase in the vacuum required to collapse the liner. As shown in Fig 1, the concepts of compressive load and residual vacuum for massage appear to be contradictory for very soft thin-walled liners. For liners with average or above average resistance to collapse, however, Fig 1 suggests that the two concepts might represent two sides of the same coin.



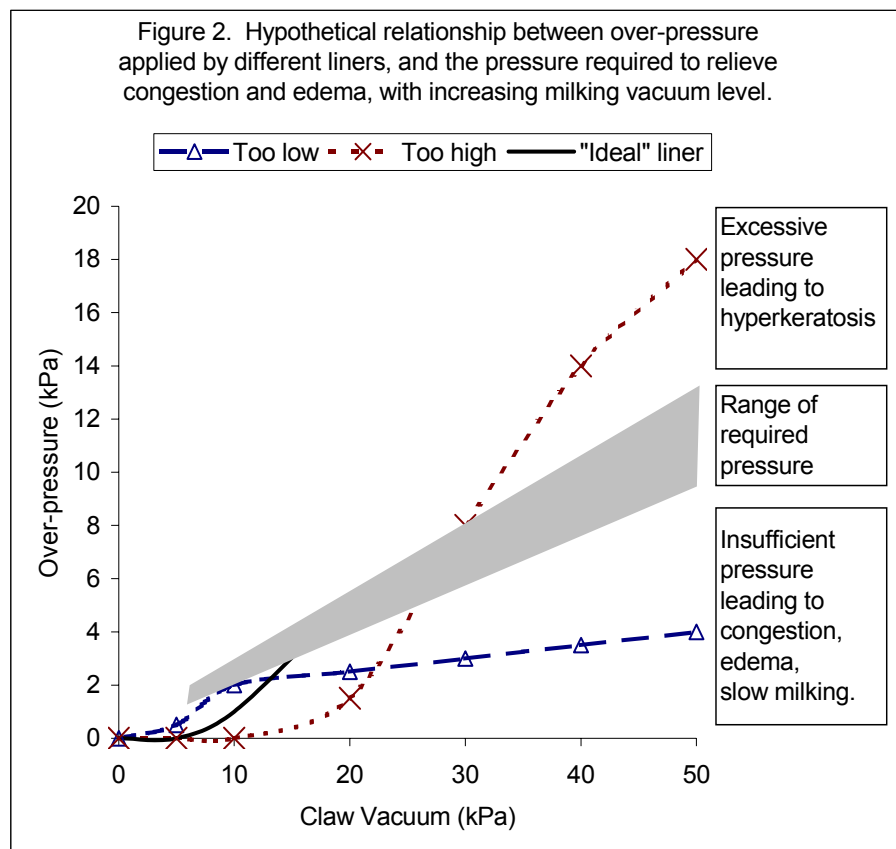
How can Over-Pressure (OP) be Measured and What OP is Required?

The average OP can be estimated by measuring the vacuum level in the teatcup pulsation chamber at which milk flow just starts or stops within a pulsation cycle. The point at which milk starts or stops flowing occurs when the compressing force applied to the teat by the liner walls is exactly balanced by the distending force induced by the vacuum level within the liner. Starting from this equilibrium point, the increase in pressure applied to a teat is approximately equal to

the incremental increase in pressure difference across the liner wall when the teatcup pulsation chamber is brought to atmospheric pressure. If the pulsation chamber vacuum is 14 kPa (4 inHg) when milk flow is just stopped by the closing liner, for example, then the average over-pressure will be about + 14 kPa during the D-phase of pulsation (Mein, 1992).

To make the measurement, a pair of liners is disconnected from the normal pulsation system and the short pulse tube is connected temporarily to a hand-operated vacuum pump and digital vacuum gauge by means of a small three-way tap. The liners are opened slowly by using the hand-pump to evacuate the pulsation chamber. The vacuum level at which milk starts to flow from each teat is noted on the digital gauge (Mein, 1992). An alternative method, which involves control and progressive reduction of the maximum vacuum in the teatcup pulsation chamber until milk flow stops, is described elsewhere (Mein *et al.* 1987). Because the OP is influenced by teat size and depth of teat penetration into the liner, measurements should be made on one or two teats of at least 10 different cows, preferably at a standard time of 1 min after teatcup attachment, in order to obtain repeatable average values. The effects of variations in intramammary pressure are small and can be ignored because the liner barrel has a mechanical advantage of about 10:1 relative to the diameter of the teat canal.

Using these measurement principles, the range of OPs applied by a limited group of commercial liners was estimated to be 8-12 kPa or 2.5-3.5 inHg (Mein, 1992). This narrow range, which has evolved by trial and error in thousands of herds over the past century, may indicate that such loads are sufficient to achieve the required reduction in congestion within the teat walls. In principle, the OP required to relieve teat congestion that occurs during the liner open phase of each pulsation cycle will increase with increasing vacuum level. This concept, illustrated in Figure 2, suggests that teat congestion might not be relieved adequately if the average OP is below this range (perhaps leading to more edematous teats, slower milking or petechial haemorrhages). On the other hand, OPs above this theoretical range may impede arterial inflow because the mean arterial pressure in the blood vessels of the teat is about 12 kPa (Mein *et al.* 1987). Furthermore, higher OPs appear to lead to increased levels of teat-



end hyperkeratosis as we shall see later.

Several methods have been developed for measuring the OP applied by different liners to a range of artificial teats or excised teats (Muthukumarappan *et al.* 1994; Davis *et al.* in preparation). Results obtained in these studies indicate that the liner OP applied to artificial, excised or live teats:

- increases with increasing liner vacuum primarily because of the greater pressure difference across the liner wall (Fig 2). The increase may be exacerbated by greater bending of the liner around the ends of teats that have become more congested because of the higher vacuum;
- increases markedly with higher mounting tension of the liner (Muthukumarappan *et al.* 1994) as a direct result of the increase in free surface area of the liner walls immediately beneath the teat (Mein *et al.* 1987);
- increases slightly as the C-phase of pulsation is shortened (Mein, unpublished data). More precisely, the transient peak pressure is higher when the teat-end is compressed more rapidly (eg, see Fig 3 in Mein *et al.* 1987);
- initially increases with increasing depth of teat penetration into the liner but then starts to decrease progressively to nearly zero as the teat-end nears the bottom of the liner barrel;
- increases gradually at first but then starts to decrease progressively with: 1) increasing liner wall thickness, 2) increasing rubber hardness, 3) increasing resistance to collapse (ie. higher "touch pressure") of the liner as illustrated in Fig 1. For each of these three physical factors, the eventual decrease in OP reflects the increasing resistance to bending at the edges of the closing or closed liner.

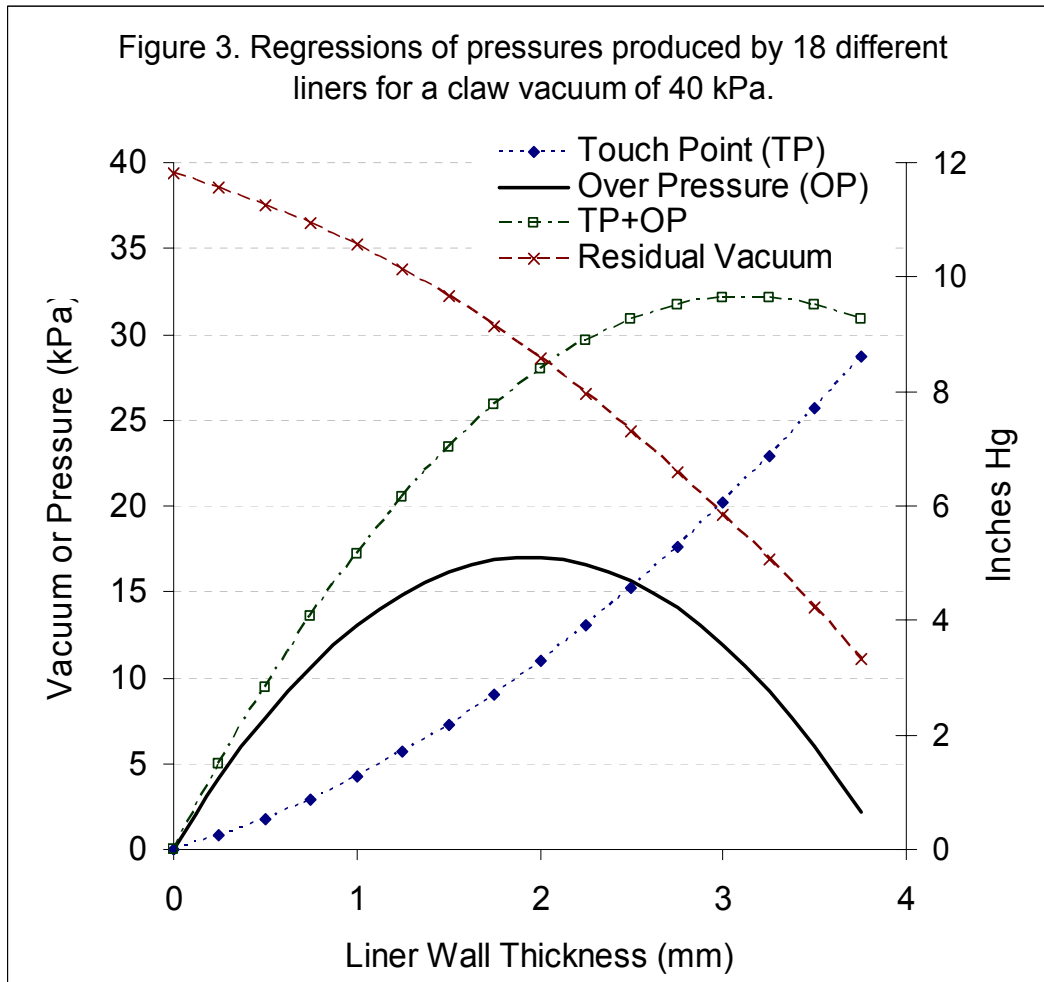
Although these relative patterns could be observed in all of the above studies, absolute values obtained with different artificial teats varied with the characteristics of the artificial teat. For example, measurements made with a small-sized artificial teat tend to be low because the liner does not have to bend as much to collapse around it. On the other hand, measurements made with an artificial teat that is harder and less compliant than living teat tissues will result in artificially high OP.

Combining the Concepts of OP, Touch Point (TP) and Residual Vacuum Available for Massage

Figure 3 offers a unified theory of the pressure applied to a teat by the closed liner. It is based on milking-time measurements of live teats at UW-Madison at a claw vacuum of 40 kPa (12 inHg) using a total of 18 commercial and experimental liners from France (Le Du and Taverna, 1989), Germany (courtesy of J. Hamann) and the USA (Muthukumarappan *et al.* 1994). Despite all the variations in liner dimensions and their material properties, these regressions had R-square values of 83% for the TP curve and 84% for the curve of (OP + TP) when plotted against the single characteristic of liner wall thickness.

If the claw vacuum is increased, then the TP curve will not change but the OP curve would be raised (thereby increasing both the liner OP and the residual vacuum for massage). If the mounting tension of the liners is increased, then the TP curve would be raised slightly while the OP curve would be raised markedly (thereby increasing the liner OP with little or no real change in residual vacuum available for massage). According to technical publications in the USA, residual vacuum should be at least 6 inHg (20 kPa). Although Fig 3 indicates that this minimum

value might be about right, it also suggests that the concept of "residual vacuum" is incomplete. A recommendation for some maximum value would be required to complete that story. Alternatively, both the liner Touch Point and the Residual Vacuum concepts could be superseded now because the concept of OP is simpler, it provides a direct measure of the true milk: rest ratio, and it has a more direct relationship with teat condition.



Where is the Maximum OP Applied to the Teat-end?

The old cine-radiographic studies by Ardran et al. (1958) provided the earliest evidence that the teat canal appeared to be closed progressively upwards from the teat orifice as the liner closes around the teat-end. This process was thought to be important as a possible mechanism for mastitis infection. These old cine films did not have sufficient resolution to show the process of teat canal closure clearly, however. Now, more than 40 years later, one of us (Williams, unpublished data) can answer this key question about teat canal closure. The canal does not close from the bottom up. It first closes near or just below the middle region of the canal. Presumably, this region is adjacent to the "meatiest" part of the teat-end where the liner encounters greatest resistance to bending and, therefore, it applies the greatest initial pressure to the teat. A series of radiographs of excised teats in a liner, mounted at different tensions in an X-

ray transparent shell, was made with the liner opened and closed. A thin-walled silastic tube (1.5mm ID x 2mm OD) was inserted through the teat sinus and teat canal. This tube was filled with mercury and the distal end of the tube was sealed. Mercury pressure in this tube within the teat canal could be adjusted by varying the hydrostatic head at the open end of the silastic tube. This series of radiographs showed that:

- the region of the teat canal that was closed first by the liner pressure was located about 25% -50% above the outer end of the teat canal;
- complete closure occurred by progressive occlusion of the mercury column both upwards and downwards from the region of initial closure;
- when the liner was mounted at higher tension, the region of initial closure was moved higher up the teat canal, nearer to the 50% position.

Because canal closure occurs, initially, some distance above the distal end of the teat canal, the implication is that **there must be an inherent dilating force at the tip of the teat.**

Responses of the Teat-end to this Applied Pressure

White teat rings and other more severe symptoms of hyperkeratosis are a direct response to the high skin stress generated by the closing liner or by a strong hand-milker or a vigorous calf. (Note: Teat rings occur in suckled beef cows too according to Farnsworth, pers. comm.). If the OP applied is greater than that required to occlude the vascular outflow pathways, then the local pressure increases because fluids cannot escape from the cul-de-sac at the tip of the teat. The local pressure difference across the teat skin will be some combination of liner vacuum plus OP and could be as high as:

$$45 \text{ kPa plus } 20 \text{ kPa} = 65 \text{ kPa} \quad (13.2 \text{ inHg} + 5.8 \text{ inHg} = 19 \text{ inHg} !)$$

Histological sections of the skin surrounding the external teat orifice often show the presence of micro-fissures. Presumably, these are generated by the high skin stress generated by milking in much the same way as human skin can be stretched, dilated and split when a pimple is squeezed. The *Stratum corneum* responds to such micro-fissures by increasing the rate of production of keratin. Thus, teat-end roughness can be regarded as an extension of the white ring effect. It appears to result from unusually high liner OP (generated, for example, by high liner vacuum, high liner tension or positive pressure pulsation) or from unusually long application of the liner OP (associated with over-milking, for example). The onset and severity of teat-end roughness is, of course, greatly exacerbated by conditions resulting in drying and hardening of the teat skin produced by harsh environmental conditions or exposure to certain chemicals.

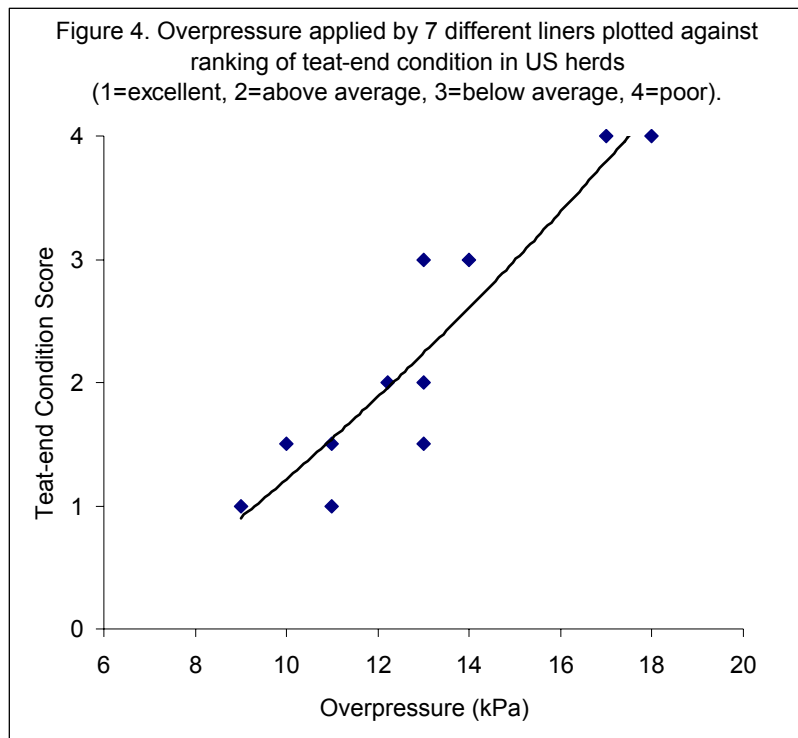
Although teatcup liners collapse by flattening the teat-end in two planes (or 3 planes in the case of triangular liners), the white ring is approximately circular because the direction of liner collapse is more or less random from one milking to the next. In addition, the internal pressure that is generated acts uniformly in all directions within the tip of the teat.

Teat congestion, edema, petechial haemorrhages and slow milking may result from insufficient OP applied by the liner. That is, the load applied may be lower than that required to alleviate the congestion generated during the liner open phase as illustrated in Fig 2.

What Happens in the "Real World"?

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. In Figure 4, their responses are plotted against the relevant OP values from Fig 3. The general relationship is clear. It suggests that liner OP values above 12-13 kPa (about 3.5-4 inHg) may be undesirable. As already noted, OP values above about 12 kPa may be unnecessary from a physiological viewpoint (Mein *et al.* 1987).

Although none of us can do much to control the over-riding effects of climate on teat-end hyperkeratosis, perhaps there is some potential for reducing the basic machine-related effects in problem herds. One obvious way to reduce the effects of liner OP is to reduce the total number of times that the liner opens and closes on individual teats each day by removing the clusters sooner. Reducing the length of the low flow period of milking and/or eliminating overmilking helps to reduce the effects of liner OP for two reasons. Firstly, the pressure difference across the liner wall is at its highest during these periods of milking when liner vacuum is highest. Secondly, the liner has to bend further to close around the end of the teat because the teat wall tends to thicken markedly during these periods of low or no milk flow.



Another way to reduce the total number of pulsation cycles per day is to adjust pulsator settings to a ratio of 65:35 while limiting pulsator rates to about 60 c/min. The increase in milk flow rate at a ratio of 65:35 compared with 60:40 is much greater than the gain resulting from a pulsator rate of 65 compared with 60 c/min. The teats of a cow with an average milking time of 5 min will be subjected to 20-25 fewer pulsation cycles per milking at a rate of 60 rather than 65 c/min.

As shown by the data in Fig 3, liners with a wall thickness between 1 and 3mm (0.04-0.12") tend to produce liner OPs greater than 12 kPa (3.5 inHg). Apart from increasing wall thickness

of their barrels to about 3.0-3.3mm (or **reducing** the wall thickness to less than 1mm), one sure way to reduce the OP of such liners would be to reduce their mounting tension by shortening their shells or by lengthening their liner barrels. Although lower tension might cause slightly slower milking, it would lead to a significant improvement in teat-end condition for some liners. Another, more radical, option would be to control the pressure difference, which is applied across the liner walls during the D-phase of each pulsation cycle, to the desired level. For example, the "fresh air" lines that supply filtered air at atmospheric pressure to the pulsator air-port(s) in many current milking systems, could be maintained at a pre-set low vacuum level (or positive pressure). If this air supply were maintained at a vacuum level of 5 kPa (1.5 inHg), then the average OP applied by any given liner would be reduced by about 5 kPa.

Conclusions

1. The skin at the tip of the bovine teat is subjected to an inherent dilating force produced by the intermittent positive pressure applied to the teat by a calf or hand-milker, or by the "over-pressure" (OP) applied by the teatcup liners in all conventional milking machines.
2. The dilating force applied to a teat-end within a teatcup liner is higher when the liner is closed than when it is open. It increases when teats are milked at higher vacuum or with alternating (2x2) pulsation compared with simultaneous (4x1) pulsation because the pressure difference is higher across the liner walls during the D-phase.
3. OP is a better and more direct indicator of the likely effects of machine milking on both teat condition and milk: rest ratio than the liner "touch point" or "offset".
4. The OP applied to cows' teats by different liners appears to range from less than 3 kPa (about 1 inHg) up to more than 20 kPa (6 inHg) for exactly the same pulsator settings.
5. Liner OPs less than about 8 kPa (2.5 inHg) are likely to be too low to relieve the degree of teat congestion and edema induced by a claw vacuum of 40 kPa (12 inHg).
6. Some commercial liners apply an un-necessarily high OP to the average cow's teats. Liner OPs greater than 13-14 kPa (about 4 inHg) are likely to be associated with poorer teat-end condition scores (that is, with more hyperkeratosis).
7. The onset and severity of teat-end hyperkeratosis is profoundly affected by the over-riding effects of climate, seasonal and environmental conditions, milking management, herd milk production level and genetics of individual cows.
8. If desired, the simplest and most effective ways to reduce machine-related hyperkeratosis would be:
 - to reduce the machine-on time per cow, especially during the periods when milk flowrate is less than about 1 kg/min and the times when average claw vacuum is above about 42-45 kPa (12.5-13.5 inHg);
 - to reduce the total number of pulsation cycles per milking by optimising the pulsator rate and ratio;
 - to reduce the mounting tension of some high-tensioned liners;
 - to control the pressure difference applied across the liner walls during the D-phase of pulsation.
9. The optimum liner OP required to alleviate teat congestion resulting from the distending forces applied to a teat when the liner is open (for any given set of milking conditions) could be determined by measurement of the change in thickness of teats after milking, relative to the pre-milking values for individual teats (Hamann and Mein, 1996).

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