Unraveling the mysteries of liner compression

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What is Liner Compression?

Liner compression (LC) is the mean compressive pressure (expressed in kPa above atmospheric pressure) applied to the inner tissues of the teat apex by the liner during the d-phase of pulsation. One component of LC has been defined as Over-Pressure (OP) by Mein et al. (2003) as the mean compressive pressure, above that required to just start or stop milk flow from the teat, which is applied to the inner tissues of the teat apex by the liner during the d-phase (Figure 1). Note that the method used to measure the OP values quoted in this paper is done in a somewhat different way (Gomez, 2010) than the method previously reported by Mein et al (2003). Our new method (OP2) is a ‘dynamic’ method in which pulsation continues throughout the test while the pulsation chamber vacuum is increased in steps of 2 kPa until milk flow is observed. The previous method (OP1) stops pulsation by removing the short pulse tube from one teat cup. Vacuum is then slowly increased until milk flow is observed. OP1 provides a very long d phase of pulsation followed by a slow removal of LC as PCV is increased. OP2 provides continuous pulsation with gradually increasing LC. The OP2 method produces values about 66% of the OP1 method. This must be taken into account when referring to previous recommendations for OP made with the OP1 method.

Figure 1. 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). From Mein and Reinemann (2009).
Another method to estimate the relative LC of different liners, or individual liners used at different milking vacuum levels, is the Residual Vacuum available for Massage (RVM). This value is obtained by subtracting the vacuum required to collapse the liner (i.e., the liner ‘Touch Point’) from the average claw vacuum (figure 1). 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. 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. This measurement was developed for round liners, which exhibit ‘buckling’ behavior when they collapse. The measurement is easy to make and quite repeatable for round liners. It cannot be applied to triangular and square liners, as the opposing walls of these liner shapes never touch. The ‘touch point’ of the adjacent walls of triangular or square liners is a much more subjective, and therefore less repeatable, measurement and cannot be used as a comparable measurement to the touch point in round liners. We have found that while OP and RVM are correlated, there are substantial differences between these two estimates of LC, especially for certain liner types.

There have been numerous attempts to develop sensors to measure LC and/or some of its components. The measurements resulting from artificial teat sensors are highly depended on the measurement technology used. These artificial teat sensors have provided valuable information on the relative components of LC as influenced by

- Material properties of the liner
- Liner tension
- Pressure difference across the liner during the d phase of pulsation
- Liner shape

A summary of these terms and the influence of liner properties on LC effects are presented by Mein and Reinemann (2009).

Sensors have also been developed to measure local pressure at the teat-liner interface. LC is NOT the same as point pressures measured in this way. These sensors typically respond to both forces that can be transmitted to the inner teat tissue as well as the shear force developed at the teat/liner interface and these two components are usually not differentiated. Point measurements made with a flexible sensor (usually using capacitance devices designed to measure normal forces) can be more than 10 times higher than sensors designed to measure LC and estimates made using OP. This is likely because these flexible sensors are designed and calibrated to measure normal force while signal generated by shear force is greater than the signal generated by normal force.

Teat length, diameter and shape affect LC. For example, short teats may experience a lower LC because the liner cannot apply much compression when it does not have to bend so far to collapse beneath the teat. Very short teats may not even penetrate the liner into its zone of collapse and therefore receive no LC during milking. 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.

**Why is it Interesting and/or Important?**

One purpose of pulsation and LC is to relieve congestion in teat tissues during milking. Vacuum is applied to the teat end during the entire pulsation cycle and also applied to the teat barrel depending on how well the teat barrel seals in the liner barrel. If the teat barrel does not fill the liner cross section, more vacuum will be developed in the liner mouthpiece and expose more of the teat to vacuum levels
approaching the claw vacuum. Vacuum applied to teat tissues is the driving force behind teat tissue congestion. As the vacuum level increases and as more of the teat surface is exposed to vacuum, the faster and more severe will be the resulting tissue congestion. The teat-end experiences no LC during the b-phase and the longer the liner is left open, the more teat-end congestion will occur.

LC is applied only to the teat end: the lower 10 to 25 mm, depending on the liner type and teat shape. The teat walls surrounding the sinus receive little or no LC. LC is effective, therefore, at relieving teat end congestion, but not congestion in the teat wall or at the base of the teat. Effective reduction of teat-end congestion results in dramatic increases in the peak milk flow from a teat during the b phase of pulsation and increasing LC generally results in higher peak and average milk flow rates.

Another result of LC is that the skin at the end of the teat is compressed and stretched during the d phase of pulsation. LC is most important machine effect on the the development of teat end hyperkeratosis or roughened teat ends.

Choosing a liner and the appropriate vacuum level and pulsation settings is an exercise in balancing the fundamental goals of milking quickly and gently. Too little liner compression results in teat end congestion during milking and slower milking. Too much liner compression results in excessive teat-end hyperkeratosis and provides no additional benefit in relieving teat end congestion. Just-right liner compression relieves the congestion at the teat-end and results in minimal teat end hyperkeratosis, reasonable milking speed and improved cow comfort during milking.

Practical Applications of this Knowledge

The 2007 revision of International Standard ISO: 5707, Milking Machine Installations – Construction and Performance, states “The user's manual shall include... sufficient data to be able to choose the liner for a herd,” and “the desired average liner vacuum and/or the desired average liner vacuum during phase b and phase d of the pulsation chamber vacuum records.” Recent research at the University of Wisconsin Milking Research and Instruction Lab has been conducted to investigate the interaction between liner properties (liner compression, dimensions, materials and shapes) and milking machine settings (vacuum level and pulsation phase durations). The methods developed to predict liner performance can be used by milking machine manufacturers and field advisors to provide guidance to users to choose liners and milking machine settings to balance the goals of milking quickly, gently and completely.

Liner dimensions

The most important aspects of fitting the liner to the cow are the physical dimensions of the liner compared to the physical dimensions of the teat. The most important liner dimensions for liner fit specified in ISO 3918 are:

- Mouthpiece and mid barrel liner diameter
  - Mouthpiece and mid barrel diameters range from just under 20 mm to over 30 mm for commercial liners.

- Mouthpiece Chamber (MPC) Depth, or the distance from the top of the liner to the highest point that the liner is able to fully collapse
  - MPC depth for commercial liners ranges from about 20 mm to over 45 mm.
The teat is remarkably adaptable in its ability to conform to a liner. Most liners have little or no ability to adapt to different teat sizes. Since we know that there will always be a range of teat size and shape in any herd, the best liner is the liner that will perform well over the widest range of teat sizes.

In order for the liner to apply compression to the end of the teat, the teat-end must be positioned in the part of the liner that is able to collapse and provide this compression. Teats stretch about 40% from their resting length to their length when situated in a narrow bore liner during milking. If we want to like apply compression to the lower 25 mm of the teat, a liner with a mouthpiece depth of 30 mm will apply full compression to teats that are longer than about 39 mm [minimum teat length = (MPD (mm) + 25mm)/1.4].

There has been a general trend toward breeding for short teats and first lactation cows have the shortest teats in any herd. American herds typically have about 25% of teats shorter than 39 mm. A liner with mouthpiece depth of 30 mm will thus result in excessive teat end congestion in about 25% of cows in the typical American herd. In addition to the problems generated by insufficient LC, these short teats will also be milked with high mouthpiece vacuum, as the teat is not long enough to create a seal in the liner barrel. The result of this will be ‘ringing’ at the base of the teat and congestion and edema at the base of the teat as indicated by intense red and blue coloring of skin at the base of the teat.

The relative diameter of the teat compared to the liner barrel also plays a role in the MPC vacuum during milking. Teats can stretch in both directions: they can get ‘fatter’ and ‘longer’. The total volume of the teat in the liner is relatively constant so if teats get ‘fatter’ they will not elongate as much. Wide bore liners (liner bore diameter greater than teat diameters) will cause teat to get fatter and reduce the ability of the teat to elongate into the zone of effective compression. This increases the minimum teat length that can be effectively massaged during milking.

**Mouthpiece Chamber Vacuum**

The vacuum developed in the MPC plays a major role in the development of congestion in the teat wall and formation of rings at the base of the teat. Teat wall congestion and teat ringing can also have a significant influence on the ease of unit removal. Our research on liners has indicated that liners with low MPC vacuum reduce the occurrence of ringing and blue teats after milking. In addition these liners also result in conditions that make unit removal much easier. If teat barrels in the MPC region become congested, the “rings” at the base of the teat act to hold the liner on the teat even after vacuum is removed from the claw.

**Liner Compression and Teat-end Hyperkeratosis**

The primary milking machine influence on teat-end hyperkeratosis is LC (environmental conditions and teat size and shape also have a large influence but are not ‘adjustable’ in commercial herds). LC for any individual liner will also increase with the milking vacuum level at which it is used because the pressure difference across the liner is increased during the d phase of pulsation. The most reliable relative indicator of LC for liners milking real cows is the OP as defined above. OP can be measured in the field without specialized sensors and is a more biologically relevant indicator of LC than RVM. OP measurements on a range of commercial liners are presented in Figure 2. The greatest OP values are more than 6 times the lowest OP values over this range of commercial liners. These OP values are highly correlated with teat end hyperkeratosis scores in field studies. In a survey of commercial farms in Wisconsin, liners with the highest OP measurements produced in excess of 80% of teats that were
roughened and cracked while liners with the lowest OP measurements produced less than 20% of teats that were roughened and cracked. Lower OP results in less hyperkeratosis or teat-end roughness.

**Figure 2.**
*Overpressure in 16 different liners using method OP2*

<table>
<thead>
<tr>
<th>Dynamic Start of Milk Flow Measurement (kPa Overpressure)</th>
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<tbody>
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**Vacuum Level and Pulsation settings**

Vacuum level and pulsation settings must be chosen for each liner taking into account the milking technology and management on each individual farm. We have developed methods to predict the effect of milking vacuum level and pulsation settings on milking speed and teat-end congestion for a specific liner. An example of the results of one of these liner performance maps is shown in Figure 3 (a 20 mm bore triangular liner fitted with a vent in the mouthpiece, OP of 5 kPa and mouthpiece depth of 27 mm). This information has been previously unavailable to milking managers and we hope that these methods will be used to take some of the mystery out of milking.

The liner performance map illustrated in Figure 3 is for one specific liner and the specific milk speed and congestion values do not apply to other liners. Liners with different shapes, materials, OP values and differing relationship between OP and claw vacuum will produce different results. There are some general trends, however, that illustrate some basic principles that likely apply to all liners.

The percentage numbers in the body of the chart relate to the relative milking speed, as indicated by average milk flow rates.

- As claw vacuum increases, so does the milking speed.
- As the b phase (milk:rest ratio) increases, so does milking speed until some critical point at each vacuum level at which point milking speed declines with increasing b phase duration due to increasing teat-end congestion.
The effects of these two machine settings are interactive: e.g. there are a number of combinations of claw vacuum and b phase duration to achieve a relative milking speed of 90% of the maximum for this liner. Which is best?

<table>
<thead>
<tr>
<th>Claw Vacuum kPa</th>
<th>&quot;Hg</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
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<td>37</td>
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The colors in the body of the chart indicate the degree of teat-end congestion for teats that are longer than about 37 mm, or enough to penetrate into the zone of effective compression for this liner (green = low, yellow = medium, red = high, purple = extreme).

- As claw vacuum increases, so does teat-end congestion
- As the b phase (milk:rest ratio) increases, so does teat end congestion

The risk of teat tissue congestion for teats shorter than the minimum length defined by mouthpiece depth is indicated by the colors in the kPa column because these short teats will not receive the full benefit of LC, as described above and congestion is influenced primarily by claw vacuum level.

As an illustration of the use of the specific liner performance map illustrated in figure 3, let us consider a milking parlor with operating vacuum of 48 kPa and claw vacuum of 42 kPa during the peak flow period of milking. Claw vacuum approached system vacuum as flow rates decline at the end of milking so that the expected claw vacuum in the low flow condition would be about 47 kPa. It is useful to measure claw vacuum during both the peak flow and low flow (just before unit removal) periods on a farm in order to assess congestion risk during all phases of milking. In this example we expect a range of 5 kPa in claw vacuum over the range of expected claw vacuum conditions.

The milking speed numbers should be interpreted using the expected claw vacuum during the peak flow period of milking (42 kPa in this example), as the peak flow period makes up the largest portion of the
total milking, especially if automatic cluster removers are used. The fastest milking condition (91% of the fastest possible condition for this liner) would occur with a b phase setting of 500-550 ms, however, the risk of teat-end congestion would be relatively high during the peak flow period (bordering between yellow and red). During the low flow period of milking (claw vacuum of 47 kPa) this pulsation setting the risk of teat-end congestion borders between high and extreme.

If gentleness were the main priority we might choose a system vacuum level of 42 kPa (range of claw vacuum from 41 kPa during the low flow period to 36 kPa during the peak flow period) and b phase duration of 450 ms. These machine settings for this liner would result in very low teat congestion during the peak flow period and only moderate teat congestion during the low flow period for most cows and would substantially reduce teat-end and teat barrel congestion for cows with short teats. The milking speed for these settings would be 80% of the maximum for this liner, or a reduction of 11% compared to the previous settings. If the average cups-on time were 4 minutes, the change in the average cups-on time would be an increase of about 26 seconds. The lower vacuum setting would also likely result in more complete milking.

We can also estimate the relative HK risk with this liner in these 2 milking conditions. This (triangular) liner has an OP value of 5 kPa and will therefore produce less teat-end HK than a liner with on OP value of 10 kPa. Liners that are designed to optimize peak milk flow rates tend to have OP values of 10 kPa or more. All of the OP measurements presented here were done using a claw vacuum level of 44 kPa. We are still working on predicting how OP changes with the pressure difference across different liner types but can make a rough estimate that OP changes by about 1/4 of the change in claw vacuum. The OP during the low flow period in our fast milking example would be about 6 kPa and about 3 kPa in the gentle milking example. We expect less HK in the gentle milking scenario.

Summary Points

- Choosing a liner and the appropriate vacuum level and pulsation settings is an exercise in balancing the fundamental goals of milking quickly, gently and completely.
- Liner dimensions play a critical role in determining the range of teat sizes that can be effectively massaged. The most important of these dimensions is the depth of the mouthpiece followed by the liner bore.
- Overpressure (OP) is the most practical and biologically relevant measure of the relative compression applied to teats by a liner.
- Increased OP (or LC) will result in increased teat end hyperkeratosis and will also increase milking speed. The operator must make the final decision on the relative importance of these two goals.
- OP and LC increase with milking vacuum level for each individual liner. The performance maps we are developing for liners indicate the practical effects of milking speed and congestion risk over a range of vacuum and pulsation settings as LC increases with claw vacuum.
- Liners and pulsation settings that maximize milking speed (especially peak flow rates) will also increase the risk of teat congestion and teat-end HK.
- Maximizing the gentleness of milking will generally result in a modest reduction (about 10%) in milking speed (cups-on time). This modest increase in cups-on time will have a smaller effect on the number of cows milked per hour, especially if automatic detachers are used and a maximum milking time is used.
• We are continuing this work and hope to publish performance maps for a range of liners with differing shape, material and OP in the near future.

Acknowledgements
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References