Where the rubber meets the teat and what happens to milking characteristics

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Abstract: The primary purpose of this review is to describe the effects of liners and pulsators on milking characteristics in ways that might improve our understanding of these interactions at the real interface between the milking machine and the cow. The results of many comparative experiments indicate that liner design usually has a greater effect on milking characteristics than any other machine factor. International definitions for critical liner dimensions should include the upper barrel bore. Barrel taper should be defined also. Guidelines for the effective collapse zone of a liner should be developed. After a century-long process of trial and error, most manufacturers now set their pulsators within a relatively narrow range to optimise milking speed. Pulsation settings that allow the pulsation chamber to return to full atmospheric pressure for at least 15%, or at least 150 ms, in each pulsation cycle help to overcome teat congestion induced by the milking vacuum.

The milking characteristics of greatest practical importance to farmers include: milk yield per cow per milking; average milking time per cow; mean strippings yield per cow or per quarter; the frequency of liner slips, cluster falls or kick-offs; teat condition and cow behaviour. Average milk yield per minute of cups-on time per cow provides a very good comparative measure of milking performance. This figure is obtained by dividing the milk yield per cow per milking by the average milking time per cow. Effects on teat condition are not included in this review because they are covered in a companion paper [1].

Effects of liners and liner design

The results of many comparative experiments indicate that liner design usually has a greater effect on milking characteristics than any other machine factor. Comparative studies in Ireland showed six-fold differences in strippings yield, eight-fold differences in the incidence of teatcup slips, and 33% differences in milking times between liner types [2]. Comfortable liners minimise the risk of teat damage, thereby encouraging better cow behaviour throughout milking. In theory, liners of all types are designed to:

1. provide a mouthpiece and barrel of a diameter that will fit a range of teat shapes and sizes, thereby minimizing liner slips and cluster falls;
2. provide a zone of effective collapse along the barrel of the liner to ensure adequate massage for the majority of teats;
3. milk as quickly and completely as possible, minimizing teat congestion, discomfort, and injury;
4. clean easily.

In practice, however, liner design is often a series of compromises or trade-offs between competing goals. For example, a liner designed primarily to reduce cup slips may be less comfortable for cows [3]. A liner designed primarily for fast milking tends to leave more milk behind as "strippings" trapped in the udder cisterns [4].

Physical features of liners and main effects on milking characteristics

Amongst the hundreds of designs available throughout the world, the diameter of the mouthpiece lip ranges from 18-26mm, the mid-bore of the liner barrel from 18-30 mm, and the effective length of the liner from about 90-164mm [5]. Some important dimensions and terms used for characterising a liner are shown in Figure 1. Small changes in the material properties of liners or changes of only 1-2mm in their physical dimensions can have a remarkably large influence on their milking characteristics.

1. ***Rubber type and composition***. Liners are made of natural, synthetic (usually nitrile) or silicone rubber. These properties affect the useful working life of a liner, which is usually measured in the number of 'cow-milkings'. Liners made of natural rubber have a working life of about 600-800 cow-milkings. Outside of the USA, most liners made of nitrile rubber or natural/nitrile blends can be used for 2500 cow-milkings or 4-6 months, whichever comes sooner. Nitrile rubber or natural/nitrile liners made or used within the USA have an effectively life of only about 1200 cow-milkings because the USA has imposed a limit on the carbon black filler content of such liners. Although silicone rubber liners are more expensive initially, they last longer. Individual manufacturer's claims vary from 3000-5000 cow-milkings (or 4-6 months, whichever comes sooner) or 1500 working hours; or up to 10,000 cow-milkings, presumably depending on the type of silicone used.

2. ***Method of construction***. Most liners are made in either one-piece or two-piece designs. A two-piece liner has a separate short milk tube. Nowadays, many farmers choose one-piece moulded liners, mainly because they are easier to assemble and simpler to change when due for replacement.

3) ***Barrel size.*** Liners are commonly described as wide, medium or narrow-bore. In the USA, a liner described as "wide-bore" usually has a bore greater than 24 mm (the diameter of a US 25 cent piece), and a "narrow-bore" liner has a bore size less than 21 mm (the diameter of a US nickel). In practice, it seems more sensible to relate these classifications of "wide-bore" or "narrow-bore" to the average teat size for a given herd. For example, a liner could be defined as "wide-bore" if the internal diameter of its mid-barrel (measured, according to ISO 5707:1996, at a point 75mm below the mouthpiece lip) is > 1 mm larger than the mean teat diameter measured at the mid-point of the teats. Similarly, a liner could be defined as "narrow-bore" if its mid-barrel bore is > 1mm smaller than the mean teat diameter. Such a definition raises other questions and concerns, however.

    1. Mid-barrel dimensions are meaningless on their own. It would be more sensible to specify the upper barrel bore as well as the mid-barrel or the lower barrel bore so that the degree of tapering of the barrel is known. Tapered barrels tend to "fit" a wider range of teat sizes and shapes. In most liner types, the upper-barrel is 1-2mm wider than the mid-bore. In some highly tapered liner types, however, the difference is as much as 3-4mm. Tapering of the liner barrel is reported to reduce the frequency of teatcup slips and falls while also giving relatively low strip yields [6].
    2. The mid-point of most bovine teats never stretches far enough to reach the specified ISO measurement point for any liner (75 mm from the top). For these two points to coincide, a teat would have to stretch and penetrate to a depth of about 150mm into the liner!
    3. A 30-35% increase in the diameter of the end of the teat is required to allow the teat canals of most bovine teats to fully unfold within the open liner [7]. Instead of measuring the average diameter at the mid-point of the teat, therefore, it would make more sense to measure the average diameter of the teat-end at about 10-15 mm above the tip. The purpose of this measurement would be to ensure that the teat canal is able to open fully without being constricted by the liner diameter.

To summarize the options, it seems clear that the ISO definitions for critical liner dimensions must include the upper barrel bore (see Figure 1). The next question is whether the barrel taper should be defined by specifying the mid-barrel bore (at the present ISO position of 75mm below the liner lip, for example) or the lower barrel bore or at both positions. We know that teats stretch to about 140-150%

of their pre-milking length as soon as the teatcups are attached. We also know that an average teat length of about 55-60mm, measured just before milking, is typical for many herds throughout the dairy world. The upper part of the teat-end (that is, 10-15mm above the tip) of teats that are 55-60mm in length will penetrate to a depth somewhere near the 75mm mark. Therefore, there is at least a reasonable basis for retaining the present ISO definition of the mid-barrel bore measured at the 75mm mark.

A mid-barrel bore of about 22mm appears to allow the teat canals of most cows to open fully while also limiting the tensile stress applied to the tissues of the teat wall [7]. Other things being equal, increasing the mid-barrel diameter by 1 or 2mm to milk cows with teats of "average" size would result in:

- fewer teatcup slips and falls (except on tight-uddered, small-teated cows)
- higher strip yields, because the liner tends to crawl higher up the teat
- increased teat congestion and oedema (which implies less cow comfort).

Similar effects to the three listed above are associated with any of the following changes in physical dimensions of liners:

- increasing the barrel diameter with respect to the mouthpiece lip diameter [8]
- increasing the bore of the upper end of the liner barrel [9]
- increasing the height of the mouthpiece cavity [10]. This distance, measured between the liner lip and the upper barrel of the liner, varies from about 18mm up to 33mm.

Variations in height of the mouthpiece cavity, as well as the extent of deflection of the mouthpiece lip during milking, influence the length of unsupported teat between the mouthpiece lip and the upper barrel. Both of these physical factors are relevant to the concept of a "zone of effective collapse length" or "zone of effective compressive load" which is discussed in the following section.

4) ***Liner length***. The zone of effective compressive load along the barrel of the liner depends on the effective length (EL) of the barrel [11] and the distance from the mouthpiece lip to the upper collapse point of the barrel. This zone of effective compressive load was defined as the "effective collapse length" by Hamann et al. [12]. The concept is illustrated in Figure 2.

As indicated in Figure 2, teats that are too short or too long for a given liner will not receive the full benefit of the intended pulsation characteristics because the liner cannot compress the teat-end. This theoretical concept is supported by measurements of the compressive load (CL) applied to an artificial teat at different depths of penetration. For example, if the maximum CL applied to an artificial teat by a Bou-Matic R1C liner is defined as 100%, then the applied CL was:

- 37% at a depth of 30mm below the upper surface of the liner mouthpiece
- 93% at 50mm and 96% at 70mm
- 100% at 90 &100mm
- 80% at 110mm and 74% at a depth of 120mm (Mein, unpublished, 2000).

It is widely accepted that liners ride higher on the teat as their bore is increased. Because the teat penetrates further into a wider bore liner [13], wide-bore liners need a longer EL. The basic physics of this phenomenon is straightforward - the bigger the liner bore, the greater the upthrust due to vacuum. In practice, however, the relationship is not quite so simple. Mean depth of teat penetration into a given liner can be reduced by increasing cluster weight [14] or it can be increased by use of liner materials with lower surface friction. According to Mein et al. [13], minimum ELs of liners made from natural or synthetic rubber should be:

- 135 mm for liners with 21-22 mm bore at mid-barrel
- 140 mm for liners of 23-24 mm bore
- 145 mm for a mid-bore of 25 mm or more.

However, these old recommendations should be reviewed and, perhaps, incorporated into a new set of guidelines based on the concept of an effective collapse zone. This would require definition of:

- a zone of ineffective massage measured from the mouthpiece lip to the upper collapse point of the barrel
- a zone of effective massage between the upper and lower collapse points of the barrel.

5) ***Liner elongation and mounting tension***. All types of commercial liners are mounted under tension in their teatcup shells because the distance between the designed support parts of the liner is shorter than the shell length. Although the elongation of some highly stretched liners is almost 30% when they are new, most new liners are stretched (elongated) by 5-15% when they are mounted in their correct shells.

Liner barrels stretch gradually and therefore lose tension as they age. There are measurable effects on average milk flow rates, peak milk flow rates and completion of milk removal as liners approach their "use-by" date. Statistically significant differences in liner performance were apparent by 840 cow-milkings for liners formulated according to USA requirements [15, 16] or by 3000 cow-milkings for liners formulated according to EU requirements [17]. When liners were aged in the USA studies of Davis et al. [15, 18]:

- liner tension decreased by 30% with a corresponding reduction in overpressure applied to the teat;
- mouthpiece lip deflection increased by 40%;
- peak milk flow rate was reduced by 0.5 kg/min;
- average milk flow rate was reduced by 0.2 kg/min.

These results imply that the change in length of a liner, relative to the length of a new liner of the same type, could be recorded at regular intervals and used as one of several practical indicators of when it is time to replace liners. The unstretched liner length can be measured as the distance between the points at the upper and lower ends of the liner where it is supported or held by the shell (see diagram). Then, the percent liner stretch can be calculated as:

$$\frac{(\text{Shell length minus unstretched liner length}) \times 100}{\text{unstretched liner length}}$$

Another way to evaluate the matching of a liner to its shell is to measure the pull (or tension) required to stretch the liner barrel to the same length as it would be when mounted in its shell. This measurement is best done with a special test rig. The middle range of mounting tension for commercial liners is around 50-70 Newtons (N). Some low tensioned liners are as low as 25 N while some very high tensioned liners are mounted at 80-100 N. Liner mounting tension falls gradually as liners age. The change in mounting tension also could be tracked to provide an important guide for when liners should be pulled up or replaced. (Note: a weight of 1 kg exerts a pull of about 10 Newtons).

6) ***Stiffness of liner mouthpiece lip***. One technique used in liner design for reducing the frequency of liner squawks and cup slips is to stiffen the mouthpiece lip by making it slightly thicker. Various devices are used to measure mouthpiece lip deflection (often called "stiffness" or the opposite term, "mouthpiece softness"). A common technique is to measure the vertical movement of a smooth cone into the liner mouthpiece when a weight of 500g is applied to the cone. The liner is held vertically in its shell. The weight is suspended from a cord that is attached to the bottom of the cone and passed through the liner barrel and short milk tube. The cone is cut at an angle of 20 degrees and lubricated to reduce measurement variability due to friction between the mouthpiece lip and cone. In one American study, mouthpiece deflection was about 8mm for one type of "soft-lipped" liner when new. The deflection increased to 11-12mm after the liner had milked 2500 cows [16]. In a study with a

different group of liners in Ireland, the average deflection was 3.5mm, ranging from 6mm for the softest liner lip to 2mm for the stiffest liner lip [13].

Some effects of variations in liner design on their milking characteristics are listed in Table 1. A few dimensions of three different liners are given below, by way of example, to illustrate some of the broad generalisations outlined in Table 1 as well as some of the more subtle effects of liner design. These three commercial liners represent three distinctly different evolutionary pathways in the on-going search for the world's perfect liner.

- The Bou-Matic R1C liner represents an example of the narrow-bore liner family from the USA. This liner is designed to provide a close-fitting, supporting sleeve for the teat barrel in an attempt to minimise machine-induced teat congestion and oedema and to improve cow comfort.
- The SAC liner, from Denmark, is an example of the medium-bore family of liners. This particular liner incorporates a short milk tube that has an unusually large (14mm) bore to improve milk drainage from the liner barrel. The implication is that a primary design goal for this liner is to reduce the risk of mastitis by minimising cyclic vacuum fluctuations.
- The DairyMaster liner is an example of a wide-bore tapered liner from Ireland. As with the Danish liner, a primary design goal for this wide-bore liner is to minimise the risk of new mastitis infections. However, the intended pathway is quite different from the SAC approach. This Irish liner has several features that help to reduce the frequency of liner slips, thereby minimising the frequency of acute vacuum fluctuations.

Liner characteristic	Bou-Matic R1C, USA	SAC Uniflow, Denmark	DairyMaster, Ireland
Mid-barrel bore (mm)	19	22	25.6
Upper barrel bore (mm)	21.1	23.5	31.6
MP lip diameter (mm)	19.8	22	23
Ratio mid-bore:MP lip	0.96	1	1.11
MP cavity height (mm)	22	24	28.6
Limits of liner collapse zone (mm) measured from top of mouthpiece	32 (upper collapse point) to 145 (lower collapse point)	35 (upper) to 152 (lower)	45 (upper) to 151 (lower)

As indicated in this table, the USA liner has the smallest mid-barrel bore, the smallest upper barrel bore, the lowest ratio of mid-barrel bore to mouthpiece lip diameter and the smallest mouthpiece cavity height. Each of these design features is associated with less teat congestion according to Table 1.

In marked contrast, the Irish liner has the biggest mid-barrel bore and upper bore, the biggest ratio of mid-barrel bore to mouthpiece lip diameter, and the highest mouthpiece cavity. According to Table 1, each of these design features is associated with a lower incidence of liner slips. Therefore, this liner is likely to slip or fall less frequently than the other two types of liner.

Pulsators and pulsation

The main purpose of pulsation is to limit the development of congestion and oedema in the teat tissues during machine milking. In addition to, or as a consequence of, this primary function, effective pulsation helps to:

- maintain a high rate of milk flow from the teat within each pulsation cycle;
- counter the possible ill-effects of teat congestion on the level of pain or discomfort experienced by the cow;
- reduce the rate of new mastitis infections;
- stimulate milk ejection.

Many of these subtle but important effects of **pulsation** are discussed in companion papers presented at this IDF conference. Discussion in this paper is limited to the simpler and more predictable effects of changes in **pulsator settings** on the practical milking characteristics listed in our opening paragraph. Widening the pulsator ratio increases milk flowrate from the cow. This effect has been confirmed in many experiments throughout the past 50 years or more. Peak milk flow rate probably reaches a maximum level at a pulsator ratio within the range 60 - 70% depending on the characteristics of the liners used for particular studies. It is likely that the consistent reduction in flow rate at a pulsator ratio of 80% shown in Figure 3 [from ref. 19], for example, results from insufficient duration of compressive load to overcome the teat congestion that was induced while the liner was open in each pulsation cycle.

Increasing the pulsator rate generally increases peak milk flow rates. Thiel et al. [20] developed an ingenious but cumbersome apparatus to demonstrate the progressive increase in instantaneous milk flow rate over a range of pulsator rates from 0 up to 130 c/min . Fifteen years later, the physiological basis for the results published by Thiel were established by Williams et al. [21].

The perennial question about the relative merits of simultaneous versus alternating pulsation still cannot be decided with any certainty. The fact that millions of cows are milked every day with both types of pulsation, indicates that any differences are small and likely to be more or less irrelevant. This conclusion is supported by a recent study with one type of cluster in Ireland. O'Callaghan [22] showed that milking times per cow were similar with simultaneous and alternating pulsation patterns and that altering these pulsation characteristics had a minimal effect on the percentage of cows that experienced liner slips.

After a century-long process of trial and error, most manufacturers now set their pulsators within a relatively narrow range. This is mainly because milking speed is optimised when the liner is held open for about 0.5-0.6 sec in each cycle [21]. Furthermore, pulsation settings that allow the pulsation chamber to return to full atmospheric pressure for at least 15% of each cycle, or at least 150 ms of each cycle, help to overcome teat congestion induced by the milking vacuum [23]. This is the scientific basis for current ISO specifications for the minimum D-phase of pulsation.

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Table 1. General trends in the milking characteristics of liners resulting from small variations in liner dimensions

This table is intended as a general guide only. The indicative changes should be interpreted with caution because it is often difficult to separate effects that are mutually inter-dependent. For example, the liner mounting tension must increase if the barrel wall is made thicker, unless the liner is mounted in a shorter teatcup shell.

Explanation of symbols: Milking performance is improved (+) or improved markedly (++)
Milking performance is decreased (-) or decreased markedly (- -)

Change in physical dimension (eg., by 10%)	**Most common trends for:** Milking speed	Strip yields	Cup slips or falls	Cow comfort (less teat congestion)
Mid-barrel bore is increased	+ (see note 1)	-	+	-
Upper barrel bore is increased		-	+ +	- -
Ratio of mid-barrel bore to MP lip diameter is increased		- -	++	- -
MP lip is made thicker or stiffer		-	+	-
MP cavity height is increased			+	- -
Effective collapse length is increased	+ (see note 2)			+ (see note 2)
Liner tension is increased	+		-	-
Liner wall is thickened	+ (see note 3)			
Bore of short milk tube is increased	+ (see note 4)			

Note 1. No further benefit once the mid-barrel bore exceeds the average diameter of teats in the herd.
Note 2. Little or no further benefit once EL exceeds the guideline lengths given in the text.
Note 3. Little or no further benefit above a wall thickness of about 2.2mm.
Note 4. No further benefit above about 11-12mm bore

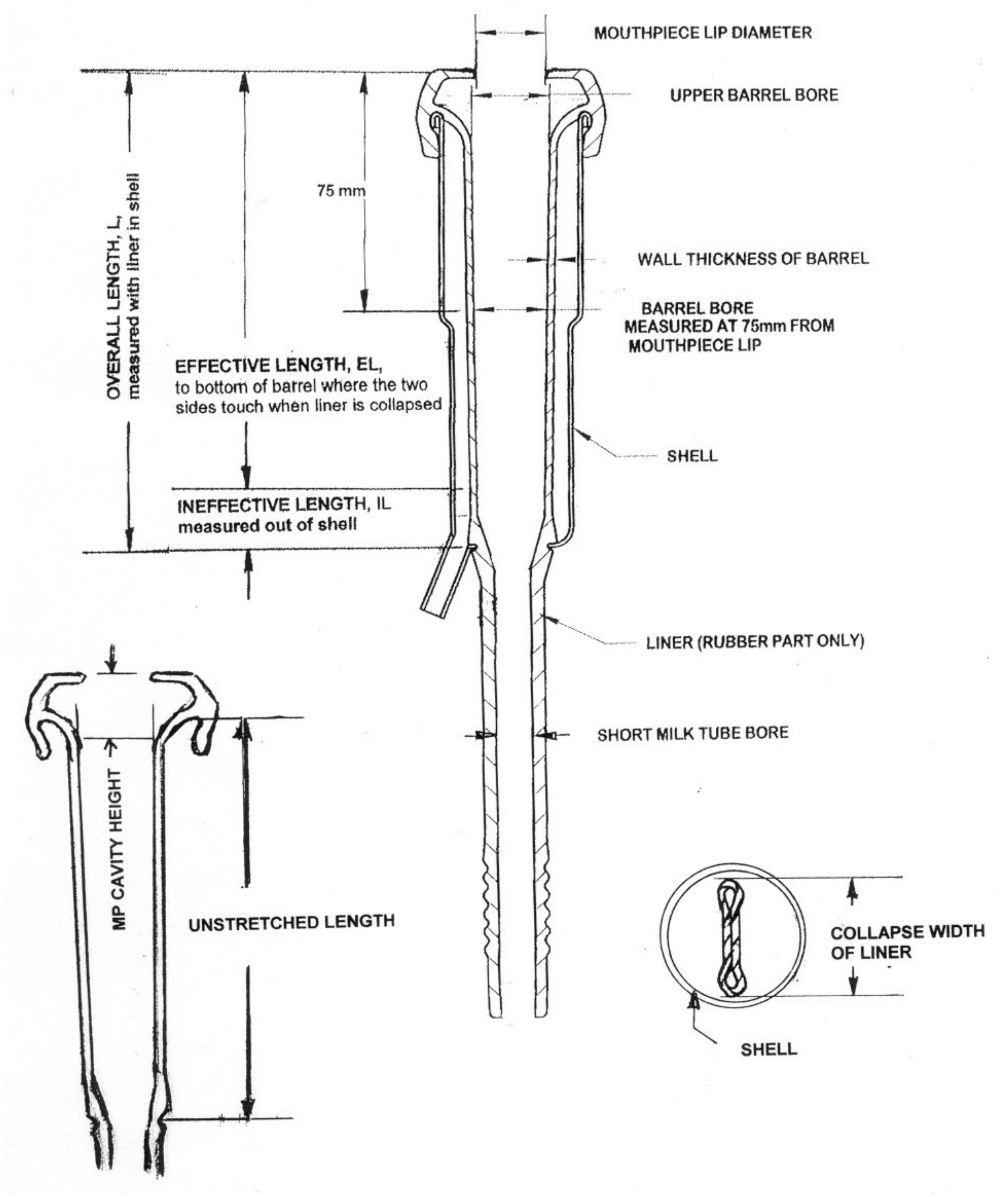

Figure 1. Some important dimensions and terms used for characterizing a liner.

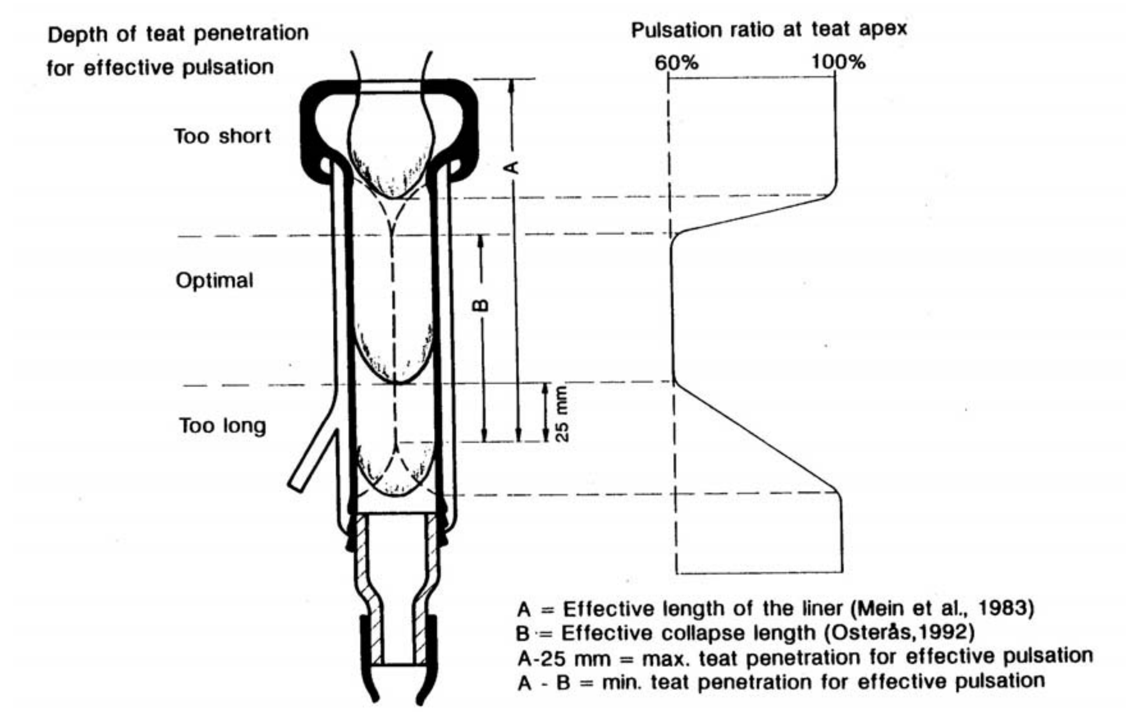

Figure 2. Changes in the effective pulsation ratio at different depths of teat penetration into a liner (for a pulsator set at a ratio of 60%)

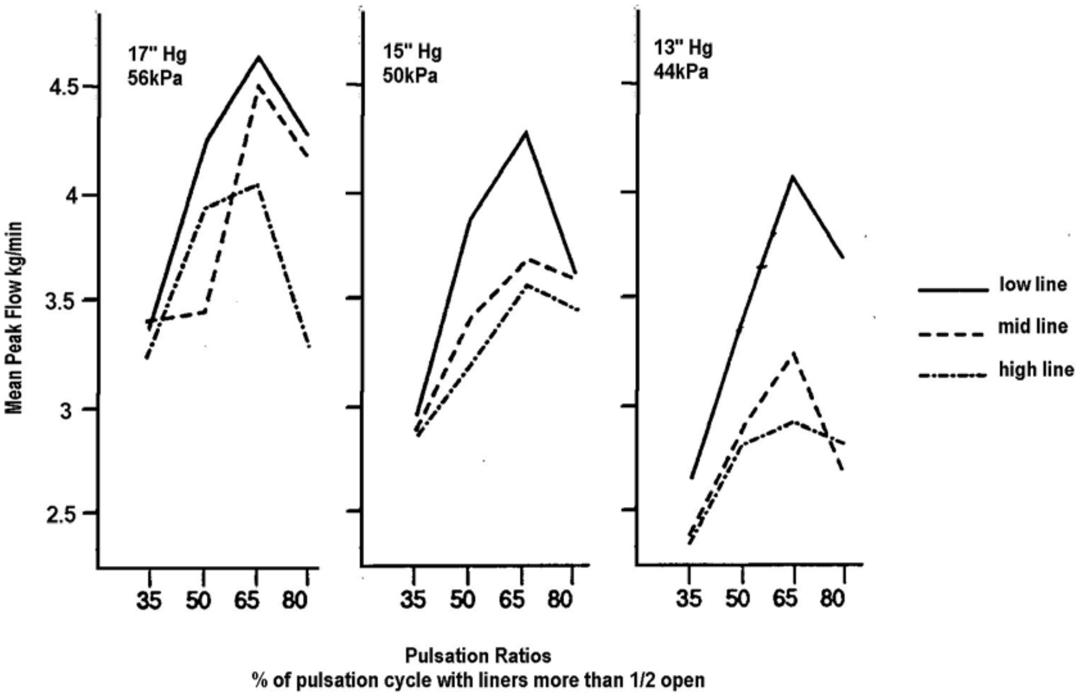

Figure 3. Mean peak flowrates of cows milked with a range of pulsation ratios, at three different vacuum levels and three milkline heights [19].