South African Journal of Animal Science 2022, 52 (No. 4)

Effects of milking machine settings and teat liners on bovine udder health

P. Vermaak, I.M. Petzer & J. Karzis[#]
Department of Production Animal Studies, Faculty of Veterinary Science, University of Pretoria, Private Bag X04, Onderstepoort 0110, South Africa

(Submitted 19 July 2021; Accepted 22 February 2022; Published 13 October 2022)

Abstract

The purpose of milking machines is to harvest milk at an optimum speed while maintaining cow comfort and preserving teat defence mechanisms against the invasion of mastitis pathogens, thus making machine settings critical in dairy herds. The various settings and combinations for milking machines were reviewed to enable operators to optimize them to preserve teat canal integrity and minimize mastitis. All databases of Web of Science and relevant websites were used to document machine settings and teat liners. All vacuum levels in milking systems need to be monitored. In addition, liners, milk yield, and automated cluster removal switch-point settings need to be regarded as bearing a risk of teat damage. They affect milking speed and vacuum levels at total, peak, and over-milking. An equilibrium should be reached between optimal milking speed and risk of teat damage. An increased switch-point setting shortens milking time and decreases overmilking and claw vacuum to preserve teat-canal integrity. Analysis of milk flow dynamics with a VaDia instrument highlights opportunities to improve milking protocols and equipment functions that align with the physiology of the cow. This knowledge can be applied on individual farms, in which herd milk yield, parlour layout, milking machine system, parlour management, and economics should be considered to obtain a balance between milking efficiency, udder health, and cow comfort. Standards for switch-point settings were identified in this review.

Keywords: automatic cluster removal, flow dynamics, milking machine vacuum, switch-point settings, udder health

Corresponding author: joanne.karzis@up.ac.za; Tel: +27 12 529 8461

Introduction

For decades, researchers have evaluated the association between milk harvesting indicators and the occurrence of clinical and subclinical mastitis (Mein *et al.,* 2012; Penry *et al*., 2017; Reinemann & Mein, 2018). It is important to have optimal milking machine functioning, timely unit attachment and detachment, a proper milk let-down, quiet cow handling, effective identification of mastitis, efficient cleaning of milking units after milking a mastitic cow, timely unit adjustment, proper alignment, and optimal nutrition (Schukken *et al*., 2003; De Vliegher *et al.,* 2018). The risk of mastitis is reduced by keeping bacterial numbers on the teat-ends low, especially if machine settings and milking management practices are not ideal (Mein, 2012; Gleeson *et al.,* 2018).

Technologically advanced milking systems are used on many commercial dairy farms in developed countries, in which settings can be manipulated by the user. Persons involved in adjusting settings must understand the effects changes might have on milking harvesting speed, teat congestion, and mastitis in the modern dairy cow. For example, there is a negative correlation between milking speed and teat congestion (Reinemann & Mein, 2011). Cole *et al.* (2020) stated that the modern, commercial Holstein cow is dried off when she is producing a volume similar to that which a cow produced at peak lactation in 1975. The same study (Cole *et al.,* 2020) found that the average lactation protein yield has increased from 225 kg in 1970 to 400 kg in 2016 in Holstein cows in the United States.

The milk stored in the cistern and alveolar tissue of the udder parenchyma can be removed by overcoming the barrier of the teat sphincter, whereas the milk in the alveolar tissue has to be moved actively to the cistern via the milk ejection reflex (Sandrucci *et al*., 2007; Jingar *et al*., 2014). Teat stimulation results in the release of oxytocin, which causes ejection of alveolar milk (Bruckmaier & Blum, 1996; Tangorra *et al.,*

URL: http://www.sasas.co.za
ISSN 0375-1589 (print), ISSN 2221-4062 (online)
Publisher: South African Society for Animal Science
http://dx.doi.org/10.4314/sajas.v53i4.02

2017); the teat canal length shortens and the cistern diameter increases, which assists in faster milk flow (Costa *et al*., 2020). Without pre-stimulation, the milk reflex is delayed. Stressful situations, inconsistent milking routine, poor cow handling, sick cows (lameness, mastitis, and systemic diseases), incorrect machine settings (such as excessive claw vacuum, a protracted vacuum (b-phase) or reduced atmospheric pressure phase (d-phase), and events such as stray voltage can inhibit the let-down reflex or prevent it from occurring. When the cow is stressed or experiences pain, pituitary oxytocin release is inhibited. The small muscles surrounding the alveoli stop contracting and milk is no longer forced from the alveoli into the milk ducts.

Bimodal milk flow is the result of interrupted milk flow prior to the oxytocin-induced alveolar milk flow (Bruckmaier & Blum, 1996; Sandrucci *et al*., 2007; Erskine *et al.,* 2019), and is detected when the drop-in milk flow exceeds 200 g/min within one minute of the start of milking (Dzidic *et al*., 2004). Bimodality may have negative effects on milking efficiency, cause an extension of machine-on time, and challenge teat and udder health because of effects that are similar to overmilking (Sandrucci *et al*., 2007; Erskine *et al.,* 2019). Good cluster alignment improves the completeness of milking and affects the precision of the automatic cluster removers (ACR) to determine the end of the milk flow (Ginsberg *et al*., 2018).

Vacuum is the main force that keeps the teat liner on the teats during milking. When the milking vacuum is lowered, liner slips may increase (Rasmussen & Madsen, 2000; Spencer, 2011). Rasmussen & Madsen (2000) recommend that the mean vacuum in the short milk tube at peak milk flow should not be lower than 32 kPa. Malfunctioning of the milking machine, that is, pulsator failure, may lead to inadequate milk removal (Penry *et al*., 2017). Overmilking refers to an extended milking time during which claw vacuum increases and fluctuations become greater (Ginsberg *et al*., 2018). This escalates the development of teat oedema and hyperkeratosis formation of callus-like tissue at the teat end and increases the risk of new intramammary infection (IMI) and mastitis (Sandrucci *et al*., 2007).

Overmilking occurs when the milk flow to the teat cistern is less than the flow out of the teat canal. This may lead to an inability to harvest 45–50% of milk within the first two minutes of milking, increasing the risk of overmilking at the end because of the late removal of clusters (Petzer & Swan, 2018). Overmilking may also occur during milking when milk flow is too fast with a high claw vacuum or when the cow is stressed or experiencing pain and adrenaline is excreted, which suppresses oxytocin and the let-down reflex. Overmilking often occurs at the end of milking when the clusters are left on for too long.

Globally, and particularly in South Africa, there is a shortage of collated, current data on milking machine settings and their effects. Such information would be useful to milk producers and dairy veterinarians. The aim of this review was to gather literature on milking machine settings and information about teat liners and their effects on intramammary infections and udder health.

Materials and Methods

A bibliographic search was performed in which full articles from scientific journals, conference papers, proceedings, and agricultural reports published from1980 to 2021 were considered. This range included primary references generated in the 1980s. The inclusion of conference papers, reports, and proceedings did not rule out publication bias. Cohort, cross-sectional, case control, and analytical studies were considered. The full text of each article was obtained where possible to discover where and under which conditions the study was done. Duplicated articles and articles not written in English were excluded. Countries and regions were neither included nor excluded.

The Web of Science was chosen as it has a wide range of databases on agricultural and medical aspects of mastitis in dairy cows. This included the Web of Science core collection, Biosis Citation Index, Cabi, Current Contents Connect, Data Citation Index, Derwent Innovations Index, FSTA–Food Science Resource, KCI Korean Science Database, Medline, Russian Science Citation Index, SciElo Citation Index, and Zoological Records. These search terms were used individually: teat liners, milking machine settings, pulsation, milking system vacuum, claw (teat end) vacuum, mouthpiece chamber vacuum, peak flow rate, liner compression, overpressure, automatic cluster removers, take-off settings, parlour efficiency, digital vacuum recorders, and milk flow. The search terms of various sub-headings were combined to obtain results.

Results and Discussion

The core purpose of milking is to harvest milk at optimum speed while maintaining cow comfort and preserving teat defence mechanisms against mastitis (Penry *et al*., 2016). The International Dairy Federation (IDF) developed milking machine standards based on ISO Standards 3918, 5707, and 6690 (IDF, 2000) that acted as guidelines. However, there is no prescribed formula for switch-point settings that can be applied to dairy parlours.

Numerous studies have shown that milking speed rises with increased milking vacuum (Thomas *et al*., 1991; Rasmussen & Madsen, 2000; Spencer *et al*., 2007), but this might increase the risk of teat congestion and microlesions of the epithelium in the teat cistern, making it susceptible to colonization by pathogens in the teat canal (Hamann *et al*., 1994; Besier *et al.,* 2015). Reinemann *et al.* (2021), found that peak flow increased by 12% when the milking vacuum was controlled, and increased only during peak milk flow, whereas the occurrence of rough teat ends was slightly reduced.

Teat liners are the only part of the milking machine that comes into direct contact with the teat. Teat liners are made of natural, synthetic (mostly nitrile), and silicone rubber. They are usually assessed by the number of milkings or by the hours they can be used. Rubber liners are less costly, but do not last as long as the synthetic blend. The lifetime of rubber liners is 600–800 cow milkings, with synthetic (blend-dependent) liners at 1200–2500 and silicone liners at 3000–5000 milkings (Mein *et al*., 2004). Teat liners on the market consist of several types of material and shapes, are non-vented or vented (in the short milk tube or mouthpiece chamber), and vary in design, liner wall hardness, wall thickness, and mounting tension (Reinemann & Mein, 2011).

Teat liners should support teat integrity and massage the teat with a compressive load (Spencer & Jones, 2000). Liner design is often a series of compromises. Liners that are designed to reduce liner slip for example might reduce cow comfort, and liners designed to milk faster may leave more milk behind in the udder cistern. Comparative experiments have indicated that liner design usually has a greater effect on milking characteristics than any other milking machine factor (Mein *et al*., 2004). Liners should fit firmly in teat cups to prevent twisting or vacuum loss from the pulsator chamber and teats should fit in the liner. The size and length of teats may vary between cows within a herd and with parity.

Anatomical and functional characteristics of teats can have a sizable influence on milk flow performance (Weiss *et al*., 2004). The classic opening and closing of the liner are important because of forced pressure differences across the wall of the liner as the pulsator operates. A cow's teats stretch up to half of their own length while milking. When a liner fits snuggly at the start of milking, it prevents much sideways stretching of the teat. A liner that is too wide allows the teat to stretch sideways and it shrinks in length. For short teats, the teat liner cannot massage them effectively during the d-phase of milking and teat congestion increases.

Teat liners must be long enough to collapse below the teat end and have a diameter of 1–2 mm less than the average diameter of the teats after milk let-down (in most cases, this will be the average teat size on the farm). The teat base diameter is measured midway from the teat length after stimulation (Reinemann & Mein, 2011). Liner fit is the most critical component of practical liner application and incorrect liner fit may cause changes to teat diameter (Reinemann & Main, 2011).

The main machine settings that affect milking speed are claw vacuum, the duration of the b-phase, and liner overpressure. Each design should have a unique liner performance map from the manufacturer (Table 1). The liner performance map in Table 1 is for a triangular liner with an overpressure of 5 kPa. The variables were teat length (below 3 cm or >3 cm), claw vacuum (34–47 kPa), and the duration of the b-phase (300–600 ms). The risk of teat congestion is indicated using a colour code. For example, at a claw vacuum of 36 kPa, a maximum milking speed of 82% can be achieved in teats ≥3 cm when the b-phase setting is 550–600 ms. At this setting, however, there is a medium risk of teat congestion. At the same vacuum level with a b-phase setting of 500 ms, a milking speed of 81% would be achieved with a low risk of teat congestion (Table 1).

Table 1 Liner performance map showing maximum average percentage flow rate. The milking speed and liner compression of a triangular liner with 5 kPa overpressure are shown.

Teat-end vacuum	**B-phase (milliseconds)**						
kPa	**300**	**350**	**400**	**450**	**500**	**550**	**600**
34	65	70	74	77	80	81	81
36	68	73	77	80	81	82	82
37	71	75	79	82	84	84	84
39	74	78	82	84	86	86	86
41	77	82	85	87	88	88	88
42	81	85	88	90	91	91	90
44	85	89	91	93	94	93	92
46	89	93	95	96	97	96	94
47	93	97	99	100	100	99	97

Colours of first column indicate congestion of teats <3 cm long	**Table colours indicate congestion for teats >3 cm long**	**Low**	**Medium**	**High**	**Extreme**

The unit of measure for all values of the b-phase is percentage (%) (Adapted from Reinemann & Mein, 2011)

A proactive udder health monitoring programme is the result of fine tuning of the general udder health monitoring programme (Schukken *et al*., 2003). Researchers have concluded that optimization of vacuum setting and liner design will improve milking time and yield (Dzidic *et al.,* 2004)

Pulsation settings on milking machines can affect milking performance (Rosen *et al*., 1983; Kaskous, 2018). Teat thickness after milking tends to increase with pulsation ratio but decreases substantially as the pulsation rate increases between 20 and 80 pulses/min (Hamann *et al*., 1994; Hamann & Mein, 1996). A pulsation rate of 50–60 pulses/min is recommended by ISO 6690:2007 (milking machine installations, mechanical tests). Thomas *et al*. (1991) indicated that the most substantial increase in milking rate was shown when the pulsation rate was increased from 20–50 pulses/min, whereas milking speed did not change with an increase from 50 to 80 cycles/min. Østerås *et al*. (1995) found that pulsation rates below 55 cycles/min affected udder health by increasing the risk of new IMI infections. In contrast, high pulsation rates of 65 pulses/min resulted in higher strip yields (Mein *et al*., 2004).

The pulsation ratio indicates the relationship between milking (milk flow) and resting (massage with no milk flow) phases and can be changed to modify peak flow rates (Hamann & Mein, 1996). Specifications for this ratio may vary between milking machine manufacturers, but normally range from a 50:50 to a 70:30 work to rest phase. The pulsator regulates the opening and collapsing of the teat liner by altering the air pressure in the pulsator chamber between vacuum (b-phase) and atmospheric pressure (d-phase) (Spencer, 2011). The main intention of pulsation is to limit congestion and oedema in the teat tissue during machine milking (Mein *et al*., 2004). Efficient pulsation also helps maintain a high milk flow, limits discomfort of the cow, reduces the incidence of new IMI, and stimulates milk ejection. Depending on the type of liner, peak milk flow reaches a maximum level at a pulsator ratio in the range of 60% to 70% (Mein *et al*., 2004). Thomas *et al*. (1991) reported shorter machine-on times and higher milk yields for wide work-to-rest ratios such as 70:30 compared with ratios of 60:40 and 50:50.

Settings that permit the pulsation chamber to resume full atmospheric pressure for at least 150 milliseconds (d-phase) during each cycle help to overcome teat congestion induced by the system vacuum (Mein *et al*., 2004). When the liner closes during milking, the critical collapsing pressure difference (CCPD) is reached. According to Spencer (2011), CCPD is 17–27 kPa, but liners than are not round in shape have a lower CCPD. The barrel wall thickness and liner tension affect the CCPD markedly, whereas rubber compounding has a relatively minor role in influencing CCPD.

Teat-end hyperkeratosis rises with increased pressure applied by teat-cup liners (Hamann *et al*., 1994) and is related to the type of milking condition and the length of the teat cup. Overpressure (compressive load) is the pressure applied to the teat by the closed liner. The touch point pressure difference is the average pressure applied to the teat by the liner as it bends around the teat within each pulsation cycle (Mein *et al*., 2003). The major factor affecting touch point pressure differences is the barrel wall thickness of the liner. The touch point pressure difference may range from 30–45 kPa (Spencer, 2011).

The milking system vacuum and the milking machine settings influence milking characteristics and the condition of teat tissue (Ambord & Bruckmaier, 2010). The vacuum pump generates a vacuum for the whole milking system (milk and vacuum lines and all devices) and determines the levels of vacuum in the claw and pulsator chamber. Milking vacuum varies because of factors such as the lifting height required for milk, milk tube length and diameter, and the numbers and types of devices incorporated into the system (Spencer, 2011; Besier & Bruckmaier, 2016). There is no single milking vacuum level that fits all systems.

A high milking vacuum (50 kPa) might increase the risk of teat tissue and canal damage and hyperkeratosis, compared with a lower vacuum (42k Pa) (Neijenhuis *et al*., 2001). The recovery time of teat tissue post-milking was also shown to increase with increased milking vacuum (Hamann *et al*., 1993). Although machine-on time decreases with a high milking vacuum, thickness of the teats, apex, and barrel size increase substantially at milking at 40 kPa and 50 kPa compared with vacuums at 25 kPa or 30 kPa (Hamann *et al*., 1993).

A low milking vacuum may reduce the effect of liner closure, resulting in less pressure during the massage phase and a higher probability of teat congestion (Neijenhuis *et al*., 2001). Low milking vacuum also increases milking duration, which might exacerbate the condition of the teat end and increase the risk of cross infection between quarters in the a-phase of pulsation (Ambord & Bruckmaier, 2010). Contrary to other studies, Besier & Bruckmaier (2016) found that a low milking vacuum of 42 kPa resulted in the teat wall becoming thicker, causing a decrease in teat cistern diameter compared to a milking vacuum of 50 kPa. Field observations from Norway found improved udder health when cows were milked at a milking vacuum of 48–52 kPa (Rasmussen & Madsen, 2000).

Claw and milking vacuum are the main forces required to keep the liner on the teats during milking (Rasmussen & Madsen, 2000). The milk tube provides a vacuum to keep the cluster on the teats and transports milk from the cluster. Vacuum drops are therefore inevitable (Besier & Bruckmaier, 2016). When a vacuum is applied to the teat, a pressure differential is created across the teat canal to remove milk during the milking phase of the pulsation cycle (Reinemann, 2013). Claw vacuum drops as soon as milk starts to flow and is transported from the cluster (Ambord & Bruckmaier, 2010). The vacuum drop is subject to increases in the milk flow rate and technical characteristics of the milking system (Besier & Bruckmaier, 2016). The highest vacuum drop in high milk-lines occurs during high milk flow rates (Besier & Bruckmaier, 2016).

In high milk-line systems, milk must be transported vertically in the long milk tube, which causes a loss of vacuum inside the milk tube, which lowers the claw vacuum (Østerås & Lund, 1980). In the absence of milk flow, claw vacuum increases to a similar level to that of the milking vacuum. In the absence of milk flow, increased vacuum would expose teats to greater risk of damage at the start (premature attachment or ineffective milk let-down) and end of milking (when milk flow declines or ceases sequentially in individual quarters) (Besier & Bruckmaier, 2016).

The vacuum loss in high- and mid-level milk-line systems depends primarily on the amount of milk transported (Ambord & Bruckmaier, 2010). During high milk flow (plateau phase), the vacuum loss is particularly high, compared with the start or end of milking when milk flow is low (Østerås & Lund, 1980; Rasmussen & Madsen, 2000; Ambord & Bruckmaier, 2010). These changes in vacuum cannot be compensated for by increasing the milking vacuum. A drop of the claw vacuum during milking may reduce milking performance by reducing the efficiency of milk removal and the vacuum level at the claw (Besier & Brukmaier 2016; Rasmussen & Madsen, 2000).This may compromise the teat condition owing to impaired liner closure and reduced pressure of the liner on the teat, hence reducing the massage effect of the closed liner on the teat (Hamann *et al*., 1993). Besier & Bruckmaier (2016) suggest that if a minimum claw vacuum is to be maintained during maximum milk flow and vacuum drops, the system vacuum must be adjusted to an appropriate level.

Using ultrasound, Besier & Bruckmaier (2016) investigated the effect of high milking vacuum on claw and pulsator chamber vacuums and their influence on milking performance and teat condition. The vacuum in the pulsator chamber did not change during milk flow, whereas the claw vacuum did. These results indicate that low claw vacuum influences milking performance, independent of the milking vacuum. Teat condition, however, is dependent mainly on the milking vacuum, and the teat tissue load is increased at a higher milking vacuum (50 kPa) at the end of milking when milk flow decreases (Besier & Bruckmaier, 2016). Therefore, ACR should be considered to limit the effects on the teat tissue and minimise milk loss with shorter machine-on time by avoiding the lowest milk flow at the end of milking.

Low claw vacuum causes liner movement within each pulsation cycle, which leads to a prolonged liner-open phase. This means that the liner opens earlier during the evacuation phase of the pulsation chamber (a-phase) and closes later when the pulsation chamber is ventilated (c-phase) (Spencer & Jones, 2000). In addition, a drop in the claw vacuum may increase the probability of liner slips because the adhesion of the liner to the teat is reduced (Spencer, 2011; Besier & Bruckmaier, 2016; Rasmussen & Madsen, 2000). The vacuum fluctuations at the teat end also depend on the technical characteristics of the milking system and increase with enhanced milk flow rate.

Claw vacuum may influence milking performance and the condition of the teat tissue parameters (Besier & Bruckmaier, 2016). In a two-chamber milking unit, the pulsation chamber is exposed to either the pulsator chamber vacuum or to atmospheric pressure because pulsation allows the liner to alternately open and close (Neuheuser *et al*., 2017) and to apply pressure on the teat end (Besier & Bruckmaier, 2016). The role of the pulsation chamber vacuum is to open the liner to allow milk flow when under vacuum and to collapse the liner under atmospheric pressure. During normal movement of the liner, milk flow occurs if milk is present in the teat cistern. This is not dependent on the presence of oxytocin. Without the release of oxytocin, all milk could be removed from the cistern before successful milk ejection from the alveoli can occur (Neuheuser *et al*., 2017), leading to bimodal milk flow curves.

Neuheuser *et al*. (2017) studied manual pre-stimulation during a decrease in the pulsator chamber vacuum. A milking vacuum of 42 kPa and a pulsation ratio of 60:40 were used and the pulsator chamber vacuum was reduced to 20 kPa to prevent the liner opening, leading to quick and complete milk removal compared with manual pre-stimulation. Thus, a reduced pulsator chamber vacuum is appropriate pre-stimulation in modern dairy practice. Therefore, after a quick clean, the teat attachment can be made directly to prevent bimodal milk flow curves during this period (Neuheuser *et al*., 2017).

The purpose of the mouthpiece lip is to seal at the teat base to maintain the vacuum during milking. Stiff mouthpiece lips occlude the blood supply and can cause ringing, whereas soft flexible lips allow the passage of tissue fluids in teats (Borkhus & Rønningen, 2003). The mouthpiece chamber vacuum of liners is important, but variable. Liners with shallow mouthpiece chambers have lower vacuums than those with deep chambers. Deep mouthpiece chambers may prevent teats from entering the zone of adequate liner compression when short teats are milked. A practical way to select the correct mouthpiece chamber length for a herd would be to use a calculation. For a liner with a mouthpiece chamber depth of 30 mm, teats should at least be 39 mm long (30 mm + 25 mm/1.4) The mouthpiece chamber vacuum decreases in old liners. The ideal mouthpiece chamber vacuum should be less than 10 kPa and teat congestion could develop when the vacuum exceeds 20 kPa (Reinemann & Mein, 2017).

Modification of single components can move the air and milk in the milking machine and lead to changes in the vacuum of the claw and mouthpiece chamber (Bluemel *et al*., 2016). At the start of milking, the vacuum is relatively low and stable in the mouthpiece. Towards the end, the claw vacuum generally increases; vacuum fluctuation increases noticeably in relation to pulsator frequency. High mouthpiece vacuum is associated with an increase in frequency of tissue stress, which results in a higher risk of IMI and mastitis. Borkhus & Ronningen (2003) studied mouthpiece chamber vacuums during the various milk phases. A more stable mouthpiece chamber vacuum was detected during peak milk flow, but the mouthpiece chamber vacuum and fluctuations increased because of pulsation during low flow. Some congestion and oedema of the teat end occurs at the end of peak milk flow, when teats are exposed to teat-cup liner conditions, even when universally accepted milking machine settings are used (Neijenhuis *et al*., 2001). Teat thickness varies with settings of the milking machine, such as vacuum level, volume of cluster removal, and pulsation rate (Hamann *et al*., 1993; Rasmussen, 1993; Hamann & Mein, 1996; Neijenhuis *et al*., 2001).

Neuheuser *et al*. (2017) defined peak flow rate as the maximal milk flow rate that continues for at least 22 seconds. Dodd & Neave (1951) found a strong, positive correlation between whole-udder milking rate (kg/min) and the incidence of mastitis in primiparous cows. Peak milk flow rate is affected by claw vacuum, duration of the b-phase, and the amount of liner compression (Reinemann *et al*., 2008; Bade et al., 2009). The main interactive effects on peak milk flow rate were studied by Bade *et al*. (2009) by independently controlling variables over a range of settings. They examined milking vacuums of 42–53 kPa, b-phase durations from 220–800 ms, and liner compressions of 8–14 kPa. The study found that increasing the vacuum and the b-phase duration always increased peak milk flow rate; increasing liner compression also increased peak flow rates with a greater effect at higher vacuum.

Reinemann *et al*. (2008) altered the claw vacuum while keeping overpressure at 8 kPa and b-phase length at 800 ms. Contrary to the findings of Bade *et al*. (2009), peak milk flow was reduced when claw vacuum was increased from 40–46 kPa. When the overpressure was increased to 11 kPa at a claw vacuum of 46 kPa and 800 ms b-phase duration, the peak milk flow increased; it increased further when overpressure was increased to 14 kPa. However, a critical level of overpressure between 8 kPa and 12 kPa is required to control teat congestion during milking (Reinemann *et al*., 2008). Poor teat end condition and discomfort are seen when overpressure exceeds 8–12 kPa (Mein *et al*., 1987; Reinemann *et al*., 2008).

The combined effects of liner compression and overpressure are important in obtaining a balance between gentle milking and speed of milking. Liner compression increases during milking as claw vacuum decreases. When the milking vacuum is lowered, the compressive load applied by the liner is reduced (Mein *et al*., 1987) but a lower compressive load is required at a lower milking vacuum (Hamann *et al*., 1993). Liner compression is further affected by claw and pulsator chamber vacuums, liner and teat conformation, liner design, liner wall harness and thickness, and mounting tension of the liners.

Milk is removed from the teat sinus during the milking phase. When the milk is removed, the accumulation of blood and tissue fluids in the teat tissue may initiate teat congestion and oedema (Leonardi *et al*., 2015; Upton *et al*., 2016b). Liner compression assists venous flow by removing fluids in the tissue of the teat-end (Upton *et al*., 2016b). Mein *et al*. (2003) described it as the mean compression pressure that is applied by the liner during the rest (or d-phase) to the inner tissue of the teat apex. The point pressure that is generated between the liner and the teat surface is usually much higher than liner compression. Liner compression is positively correlated with vacuum (Bade *et al*., 2009) and hyperkeratosis (Mein *et al*., 2003).

Neijenhuis *et al*. (2001) explained that congested teat canals tend to close more slowly post-milking and could result in a higher rate of IMI. Teat-end congestion can be relieved with an adequate magnitude and duration of liner compression during the d-phase of the pulsation cycle (Upton *et al*., 2016a), but only when the duration of the d-phase is sufficient (Hamann & Mein, 1988). The International Organization for Standardization (ISO) specifies a minimum d-phase of 150 ms per pulsation cycle (ISO 6690:2007). Hamann & Mein (1996) found that a d-phase exceeding 150 ms did little to decrease congestion or increase milk flow rate.

Liner compression is also a function of the physical dimensions of the liner (Leonardi *et al*., 2015), primarily wall thickness (Bade *et al*., 2009). Lower liner compression is experienced more often with soft silicon liners than with rubber liners, and it is higher in round than triangular liners. The extent of compression used on the teat by the liner influences the teat condition (Neijenhuis *et al.,* 2001), as it affects the comfort of the cow, teat condition, and peak milk flow rate.

Overpressure is the average compression pressure required to stop milk flow from the teat. It is not a direct measure of liner compression but is a biologically relevant indicator of liner compression (Leonardi *et al*., 2015). Mein *et al*. (2003) described the hypothetical relationship of the liner ‘touch point’, the residual vacuum for massage, and the overpressure applied to the teat. Some studies have shown that severe overpressure can damage the teat or lead to hyperkeratosis (Mein *et al*., 2003; Mein & Reinemann, 2009). An overpressure of <8 kPa may be too low to relieve teat end congestion. Eight to 12 kPa seems ideal and >13 kPa leads to teat end damage (Mein & Reinemann, 2009). There is low overpressure of 3–7 kPa in the teat cistern during milking (Ginsberg *et al*., 2018). Mein *et al*. (2003) concluded that a way to reduce the effects of liner overpressure is to remove clusters sooner.

When set correctly, ACRs will prevent overmilking damage (Tangorra *et al*., 2010) and improve udder health (Ginsberg *et al*., 2018; Boloña *et al.,* 2020; Neijenhuis *et al.*, 2020). In addition, ACRs increase milking efficiency. Wieland *et al.* (2020) found that milk flow increased substantially, whereas milking time, period of milking, and risk of teat damage were reduced at higher switch-point settings. Although milking time decreases, milk yield is maintained because of the shorter duration of milking when milk flow is low towards the end of the milking curve (Steward et al., 2002; Wieland et al., 2020). Krawczel *et al*. (2017) stated that standard milk flow curves may be used to determine the setting to terminate individual milkings. Tancin *et al*. (2006) divided the milk flow curves into four phases: increase, plateau, decline, and overmilking (Figure 1). During investigations at the quarter level, Ferneborg *et al.* (2018) found that the steepness of the decline phase had a critical effect on the optimal cluster detachment level and delay times.

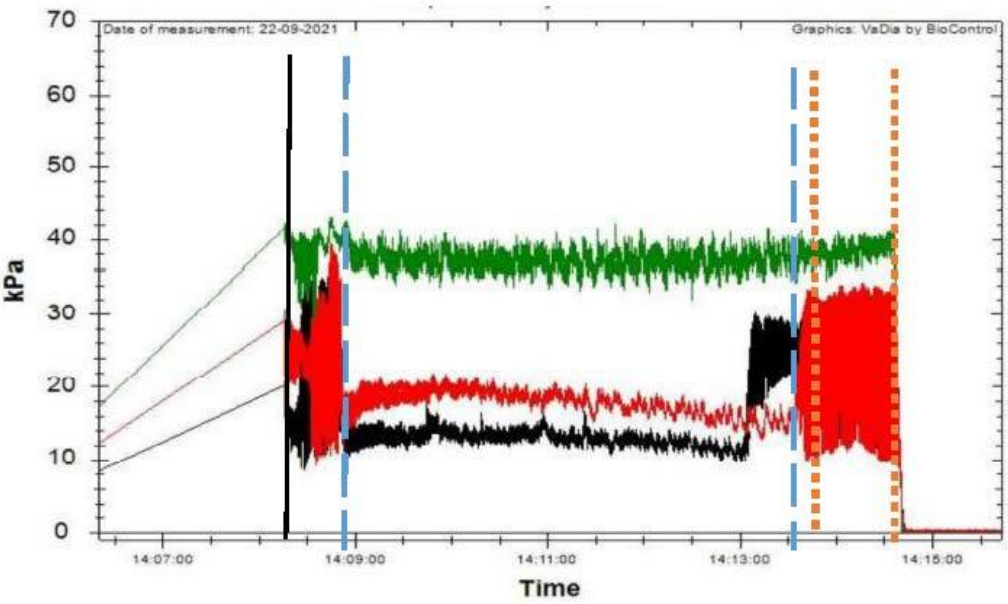

Figure 1 The four milk flow phases

The red graph represents the mouthpiece vacuum in the hind quarter. The four milk flow phases comprise the increase phase (solid vertical line to first large vertical dash line), plateau phase (area between the two large vertical dash lines), decline phase (from the second large dash line to the first dotted line), and overmilking (between the two dotted vertical lines).

The initial flow of milk (or increase phase) comes from the cisterns and large lobes. If there is no pre-stimulation, the milk flow stops after small amounts of cisternal milk (bimodal milk flow).) This is important in late lactation cows, as initial delay times may cause the ACR to remove the cluster (Ginsberg *et al*., 2018. Therefore, in herds with poor stimulation, kick-offs, and a high frequency of re-attachments, it is necessary to increase the initial delay time, which may also lead to an increase in overmilking (Ginsberg *et al*., 2018). To maximize parlour efficiency and minimize overmilking, the optimal termination point is in the decline phase of the milk flow curve, before overmilking begins (Tančin et al., 2006; Krawczel *et al*., 2017). Similarly, hyperkeratosis increases with excessively high vacuum (>50 kPa) (Spencer, 2011). Ginsberg *et al*. (2018) summarised the possible advantages of ACR as a decrease in overmilking, improved teat condition, labour saving, and a more consistent milking routine. Disadvantages of an ACR unit include the costs of installation, maintenance, and reliability (Ginsberg *et al*., 2018).

Take-off settings differ between machine manufacturers.

- Take-off limit (switch point) activates the ACR when the milk flow decreases beyond this level (Jago *et al*., 2010).
- Post milking setting is the time from the take-off limit to the time that the vacuum is cut.
- Take-off delay is the time from when the vacuum was cut until the ACR removes the cluster.
- Maximum pre-milk time and maximum second pre-milking time determine the minimum duration that the cluster is attached to the teats for the first and consecutive attachments within the same milking.
- Low-flow limit is the rate that the machine uses to change from the pre-milking phase to the main milking phase.

There are no ISO standards for ACRs that stipulate the ideal setting formulas that may be applied to specific setups (Ginsberg *et al*., 2018). Increasing the ACR threshold is an effective strategy to improve milking efficiency (cows milked per operator per hour) when the work routine times of dairy operators can be accelerated (Edwards *et al*., 2013). According to Ginsberg *et al*. (2018) and Ferneborg *et al.* (2018), in addition to the switch-point, the flow rate at cluster removal depends on final delay time and milk flow rate near the end of milking. Therefore, overmilking can occur in cows with a rapid decrease in milk flow, whereas cows with slow flow rates would be less influenced. The decline in flow rate depends on the milking vacuum (Ginsberg *et al*., 2018).

Table 2 Changes in automated cluster removal switch-point settings in the literature

References	Number of cows	Duration of study, months	Milkings per day	Threshold, g/min	Delay time, sec	Machine-on time	Milk yield, kg	Teat condition	Udder health
Rasmussen, 1993	135	36	2	200	18		NS	Improve	NS
				400	12	-0.52*			
Reid & Stewart, 1997		-	3	300–450	12–7	-1.4	Increase		
				200–900	15–3	-1.2	Increase		
Stewart *et al*., 2002	3588	2–4	2	500–640	1–1	-0.25**	0.18+		
				730–820	1–1				
Magliaro & Kensinger, 2005	60	12	2	480					
				600		-0.4**			
				800		-0.7**	-0.4**		
Jago *et al*., 2010	378	35	2	200			NS	NS	NS
				400		-0.7***			
Edwards *et al*., 2013	96	8	2	200			NS		NS
				400		-0.68***-			
				600		1.05*** -			
				800		1.20***			

NS: not significant; +: *P* <0.1; **P* <0.05; ***P* <0.01; ****P* <0.001 (Adapted from Ginsberg *et al*., 2018)

An ACR that has been adjusted for optimal milk flow threshold and delay time reduces the milking duration while maintaining milk quantity and teat canal integrity (Rasmussen, 1993). Some manufacturers enable the operators to change the take-off settings, allowing them to adapt their parlours to ensure optimum milk production. Cluster removers have promoted profitability in dairy operations by their introduction by increasing the automation of milking, decreasing labour, and improving efficiency of the milking process (Ginsberg *et al.,* 2018). Rasmussen (1993) determined that detachment of the cluster can take place at a flow rate of 0.4 kg/min. Increasing the ACR threshold level from 0.2 kg/min to 0.4 kg/min was reported to reduce milking duration without affecting milk yield, milk composition, or the incidence and prevalence of clinical and subclinical mastitis (Rasmussen, 1993).

Clarke *et al*. (2004) combined the traditional ACR milk flow switch rate with an ACR delay time (maximum cluster attachment duration) to limit the effect of the slowest 20% to 30% of cows in the herd on total milking time. This was applied successfully in late lactation, reducing the maximum milking duration of the slowest milking cows by up to 34% without loss of milk yield, increase in somatic cell count (SCC), or incidence of clinical mastitis. Jago *et al*. (2010) evaluated the effect of four criteria for determining the endpoint of milking on milk yield, milk composition, completeness of milking-out, teat skin condition, SCC, and the incidence of clinical mastitis.

The same authors showed a shorter milking time for 0.4 kg/min compared with 0.2 kg/min. No differences were found in either teat condition or the proportion of cows with at least one case of clinical mastitis during the study. Somatic cell count was low for all treatments, but highest for 0.4 kg/min. By increasing the ACR threshold setting from 0.2 kg/min to 0.4 kg/min, the milking duration was decreased without affecting production, increasing the prevalence of clinical mastitis and poor teat condition. The combination of a switch-point setting with a maximum cluster attachment time during early or peak lactation resulted in a reduced milking duration without negative effects (Jago *et al*., 2010).

In 2011, an Israeli study showed that switch-point settings above the factory default of 0.480 kg/min were present on 19 farms that used Afimilk equipment and that the default settings were not changed in only six of them. The authors concluded that a milk flow of below 0.2 kg/min was considered low for dairy cows (Ginsberg, 2011) and the cluster should be removed before such a low flow rate to prevent teat damage. Edwards *et al*. (2013) showed that clusters could be detached early without loss of milk yield. The cluster-on time of individual cows is an important factor in determining herd milking times and related labour requirements. An increase in herd size, reduction in the availability of skilled labour, and a need to minimise operational costs and improve on-farm milking practices and labour productivity (cows per labour unit) needs to be examined (Jago *et al*., 2010).

Automatic cluster remover settings can improve milking parlour efficiency and animal wellbeing. Ginsberg *et al*. (2018) recommended that clusters should be removed at a flow of more than 400 g/min, whereas Besier & Bruckmaier (2016) suggested a milk flow threshold of 1.0 kg/min. Wieland *et al*. (2018) found that a further increase in this threshold (even to 1.2 kg/min) caused a significant decrease in milking duration. Erskine *et al*. (2019) applied a threshold of 1.1 kg/min. Wieland *et al*. (2018) concluded that this resulted in a significant decrease in milking duration and improved teat tissue condition without negatively affecting milk production, milk component yields, or udder health. The risk of teat-end damage was reduced.

An understanding of how milking machine settings influence the udder milk flow rate is important for the development of best practice parameters and for appropriate sizing of milking facilities (Upton *et al*., 2016a; Upton *et al*., 2016b). The pattern of milk flow in individual quarters has four phases of intensity: incline, plateau, decline, and overmilking (Tančin et al., 2007). Quarter milk flow patterns offer biological information that is needed for improving machine milking and the welfare of cows and are thus highlighted in some studies (Tancin *et al*., 2006; Upton *et al.,* 2016b; Ferneborg *et al.,* 2018). With conventional milking machines, the entire cluster is removed at the same time, and this may result in some quarters being overmilked (Ginsberg *et al*., 2018).

Digital vacuum recorders and milk flow dynamics can improve udder health and milking efficiency by highlighting opportunities to improve milking protocols and equipment functions that align with the physiology of the cow (Sandrucci *et al*., 2007). Some instruments assess milking dynamics by measuring milk flow. The VaDia (Biocontrol, Rakkestad, Norway) records the vacuum in the milking unit and assists with the estimation of key changes in the milk flow. Its digital vacuum recorders (Biocontrol, Rakkestad, Norway) measure simultaneous vacuum events during milking in four channels while attached to the cluster (Erskine *et al*., 2019). This allows an investigator to attach and monitor numerous recorders in a milking parlour simultaneously and collect data from cows in different strings. The mouthpiece chamber vacuum is negatively correlated with milk flow and positively associated with teat congestion (Borkhus & Rønningen, 2003).

Using a VaDia, Moore-Foster *et al*. (2019) investigated whether milking vacuum measured in the short milk tube and mouthpiece chamber with digital recorders could identify key time points of phase changes in milk flow. In addition, they also studied the effect of the lag period between cluster attachment and milk let-down. They concluded that insufficient stimulation before milking resulted in delayed milk ejection and bimodal milk flow during the incline phase, which is associated with poor milking efficiency, impaired teat health, and possibly reduced milk yield (Erskine *et al*., 2019; Moore-Foster *et al*., 2019).

Malmo & Mein (2015) found a strong relationship between higher milk flow and lower milking unit vacuum being recorded simultaneously. Milk flow was measured with a LactoCorder (WMB AG, Switzerland) and milking unit vacuum, with the VaDia. Borkhus & Rønningen (2003) suggested that vacuum could be used to establish key points in the milking curve and that marked changes in mouthpiece chamber vacuum could identify phase changes of the milking curve, such as the start of overmilking.

Erskine *et al*. (2019) extended this principle to indicate the beginning of sustained milk flow after unit attachment. Their approach was supported by Malmo & Mein (2015), who found that the estimated let-down time, when measured by actual milk flow or milking unit vacuum, was highly correlated ($R^2 = 0.81$). Erskine *et al*. (2019) concluded that milk flow analysis with the small milk tube vacuum and mouthpiece chamber vacuum was a useful indicator of delayed milk ejection and bimodality. This also assisted in estimating let-down time in a herd milking three times per day since milk yield is negatively associated with increased let-down time.

In South Africa, many swing-over parlours have been installed in large dairy herds with the flowmeter far above the cow's udder, and the long milk tubes have many flow restrictions, which would increase the delay in ACR activation. These milking systems increase the risks of overmilking and of IMI. There are ISO guidelines for milking machine installation, construction and performance, but currently there are no such guidelines for ACR switch-point settings. Thus, most farmers use default milking machine settings. On the routine milking machine test, pulsographs are generated and second minute teat-end vacuums are measured.

At present, liner effects, liner fit, mouthpiece and pulsator chamber vacuums, and flow dynamics are not monitored. In future, the testing of the efficiency of the ACR switch-point settings should be included in the routine testing of milking machines. Currently, there is a desire to shorten the milking time. However, a negative correlation between milking speed and teat canal health has been determined.

Conclusion

Automated cluster removal switch-point settings should be increased to improve milk yield during the first two minutes of milking. If this is done instead of increasing the milking vacuum and the b-phase, teat canal health would also improve. Analysis of milk flow dynamics to estimate key changes in the milk flow curve could improve udder health and milking efficiency by highlighting the importance of optimum milking machine settings and use. This would improve milking protocols and equipment functions that align with the physiology of the cow. This review highlights the gap in knowledge of the correct switch-point settings that can be applied in dairy parlours. Although there are newer studies, none answers this question. The knowledge gained from this study could direct future work to optimize settings and obtain a balance between milking efficiency, udder health, and cow comfort. This could lead to the development of much-needed standards for switch-point settings.

Acknowledgements

The authors would like to thank Milk South Africa (Milk SA) for funding this study.

Author contribution

PV wrote the manuscript and conducted the research; IMP developed the concept, assisted with the research and writing of the paper, revised the intellectual content, and reviewed the manuscript; and JK assisted in with the initial composition and with the intellectual content and review of the manuscript**.**

Conflict of interest declaration

The authors declare that they have no financial or personal relationships that may have influenced them inappropriately in writing this article.

References

Ambord, S. & Bruckmaier, R.M., 2010. Milk flow-dependent vacuum loss in high-line milking systems: Effects on milking characteristics and teat tissue condition. J. Dairy Sci. 93**,** 3588-3594. DOI: 10.3168/jds.2010-3059

Bade, R.D., Reinemann, D.J., Zucali, M., Ruegg, P.L. & Thompson, P.D., 2009. Interactions of vacuum, b-phase duration, and liner compression on milk flow rates in dairy cows. J. Dairy Sci. 92**,** 913-921. DOI: 10.3168/jds.2008-1180

Besier, J., Lind, O. & Bruckmaier, R.M., 2015. Dynamics of teat-end vacuum during machine milking: Types, causes and impacts on teat condition and udder health – a literature review. J. App. Ani. Res. 44(1). DOI: 10.1080/09712119.2015.1031780

Besier, J. & Bruckmaier, R.M., 2016. Vacuum levels and milk-flow-dependent vacuum drops affect machine milking performance and teat condition in dairy cows. J Dairy Sci. 99**,** 3096-3102. DOI: 10.3168/jds.2015-10340.

Bluemel, F.E., Savary, P. & Schick, M., 2016. Effects of an extended c-phase on vacuum conditions in the milking cluster. Biosci. Eng. 148, 68-75. DOI: 10.1016/j.biosystemseng.2016.04.004

Boloña, P.S., Upton, J. & Reinemann, D.J., 2020. Effects of simulated quarter and udder teat cup removal settings on strip milk and milking duration in dairy cows. J. Dairy Sci. 103(5) 4446-4454.

Borkhus, M. & Rønningen, O., 2003. Factors affecting mouthpiece chamber vacuum in machine milking. J. Dairy Res. 70, 283-288. DOI: 10.1017/s0022029903006253

Bruckmaier, R.M. & Blum, J.W. 1996. Simultaneous recording of oxytocin release, milk ejection, and milk flow during milking of dairy cows with or without pre-stimulation. J. Dairy Res. 63, 201-208. DOI: 10.1017/S0022029900031708

Clarke, T., Cuthbertson, E.M., Greenall, R.K., Hannah, M.C. & Shoesmith, D., 2004. Milking regimens to shorten milking duration. J. Dairy Res. 71, 419-426. DOI: 10.1017/S0022029904000421

Cole, J.B., Eaglen, S.A.E., Maltecca, C., Mulder, H.A. & Pryce, J.E., 2020. The future of phenomics in dairy cattle breeding. Anim Front. 10(2), 37-44. DOI: 10.1093/af/vfaa007

Costa, A., De Marchi, M., Visentin, G., Concetta, C., Borhese, A & Boselli, C., 2020. The effect of pre-milking stimulation on teat morphological parameters and milk traits in the Italian water buffalo. Front. Vet. Sci. 2020. https://doi.org/10.3389/fvets.2020.572422

De Vliegher, S., Ohnstad, I & Piepers, S., 2018. Management and prevention of mastitis: A multifactorial approach with a focus on milking, bedding and data-management. J. Integrative Agri. 17 (6), 1214-1233. DOI: 10.1016/S2095-3119(17)61893-8

Dodd, F., & Neave, F. 1951. Machine milking rate and mastitis. J Dairy Res. 18(3), 240-245. DOI:10.1017/S0022029900006117

Dzidic, A., Weiss, D. & Bruckmaier, R.M., 2004. Oxytocin release, milk ejection, and milking characteristics in a single stall automatic milking system. Livestock Prod. Sci. 86(1-3), 61-68. DOI: 10.1016/S0301-6226(03)00150-7

Edwards, J.P., Jago, J.G. & Lopez-Villalobos, N., 2013. Milking efficiency for grazing dairy cows can be improved by increasing automatic cluster remover thresholds without applying premilking stimulation. J. Dairy Sci. 96, 3766-3773. DOI: 10.3168/jds.2012-6394

Erskine, R.J., Norby, B., Neuder, L.M. & Thomson, R.S., 2019. Decreased milk yield is associated with delayed milk ejection. J. Dairy Sci. 102, 6477-6484. DOI: 10.3168/jds.2018-16219

Ferneborg, S., Thulin, M., Agenas, S., Svennersten-Sjaunsa, K., Krawczel, P. & Ternman, E., 2018. Increased take-off level in automatic systems: Effects on milk flow, milk yield, and milking efficiency at the quarter level. J. Dairy Research 86 (1), 85-87. DOI:10.1017/S002202991800078X

Ginsberg, R., 2011. Influence of milk yield and take-off settings on milking parlour performance and udder health. In: Hogeveen, H., Lam, T.J.G.M. (eds) Udder Health and Communication. Wageningen Academic Publishers, Wageningen, pp 407-414. DOI: 10.3920/978-90-8686-742-4_77

Ginsberg, R., Dzidic, A., Rasmussen, M.D., Poulet, J.-L., Manninen, E., Sigurdsson, S., Tancin, V. & Bruckmaier, R., 2018. Teat-cup and cluster removal strategies for cattle and small ruminants. IDF Bulletin. 491, 11-40.

Gleesen, D., Flynn, J. & O'Brien, B., 2018. Effect of pre-milking teat disinfection on new mastitis infection rates of dairy cows. Ir Vet J. 71, 11. doi: 10.1186/s13620-018-0122-4.

Hamann, J., & Mein, G.A. 1988. Responses of the bovine teat to machine milking: Measurement of changes in thickness of the teat apex. J. Dairy Res. 55, 331-338. DOI:10.1017/S0022029900028582

Hamann, J., Mein, G.A. & Wetzel, S. 1993. Teat tissue reactions to milking: Effects of vacuum level. J. Dairy Sci. 76, 1040-1046. DOI: 10.3168/jds.S0022-0302(93)77432-9

Hamann, J. & Mein, G.A. 1996. Teat thickness changes may provide biological test for effective pulsation. J. Dairy Res. 63, 179-189. DOI: 10.1017/s002202990003168x

Hamann, J., Burvenich, C., Mayntz, M., Østerås, O. & Haider, W., 1994. Machine-induced changes in the status of the bovine teat with respect to the new infection risk. IDF Bulletin. 297,13-22.

International Dairy Federation (IDF), 2000. IDF Bulletin 358, Milking standards 1-18. Milking machine installations-mechanical tests. International Organization for Standardization, Geneva, Switzerland. https://www.iso.org/standard/37191.html; accessed June, 2022.

Jago, J.G., Burke, J.L. & Williamson, J.H., 2010. Effect of automatic cluster remover settings on production, udder health, and milking duration. J. Dairy Sci. 93, 2541-2549. DOI: 10.3168/jds.2009-2949

Jingar, S., Mahla, R.K., Singh, M. & Roy, A.K., 2014. Lactation curve pattern and prediction of milk production performance in crossbed cows. J. Veterinary Med. Article ID 814768. https://doi.org/10.1155/2014/814768

Kaskous, S., 2018. Optimization of the pulsation ration during the course of milk removal after using a quarter individual milking system 'MultiLactor'. OJAIR 6 (6) ISSN (online) 2319-1473.

Krawczel, P., Ferneborg, S., Wiking, L., Dalsgaard, T. K., Gregersen, S., Black, R., Larsen, T., Agenäs, S., Svennerstein-Sjaunja, K. & Ternman, E., 2017. Milking time and risk of over-milking can be decreased with early teat cup removal based on udder quarter milk flow without loss in milk yield. J. Dairy Sci. 100, 6640-6647. DOI: 10.3168/jds.2016-12312

Leonardi, S., Penry, J.F., Tangorra, F.M., Thompson, P.D. & Reinemann, D.J., 2015. Methods of estimating liner compression. J. Dairy Sci. 98, 6905-6912. DOI: 10.3168/jds.2015-9380

Magliaro, A.L., & Kensinger, R.S., 2005. Automatic cluster remover setting affects milk yield and machine-on time in dairy cows. J. Dairy Sci. 88(1), 148-153. DOI: 10.3168/jds.S0022-0302(05)72672-2

Malmo, J., & Mein, G., 2015. A new tool for milking-time investigations: Using the VaDia and interpreting results. In: Proceedings of the Countdown Symposium, 6 October 2015, Dairy Australia, Melbourne, Australia.

Mein, G.A., Williams, D.M. & Thiel, C.C. 1987. Compressive load applied by the teatcup liner to the bovine teat. J. Dairy Res. 54, 327-337. DOI: 10.1017/s0022029900025504

Mein, G.A., Williams, M.D. & Reinemann, D.J., 2003. Effects of milking on teat-end hyperkeratosis: 1. Mechanical forces applied by the teatcup liner and responses of the teat. 42nd National Mastitis Council Annual Meeting Proceedings, Fort Worth, Texas, 26-29 January 2003, pp 114-123.

Mein, G., Reinemann, D., O'Callaghan, E. & Ohnstad, I., 2004. Where the rubber meets the teat and what happens to milking characteristics. In 100 years with liners and pulsators in machine milking. IDF Bulletin. 388, 431-446.

Mein, G.A., 2012. The role of the milking machine in mastitis control. Vet. Clin. N. Am. - Food Anim. Pract, 28(2) 307-320. DOI: 10.1016/j.cvfa.2012.03.004

Moore-Foster, R., Norby, B., Schewe, R.L., Thomson, R., Bartlett, P.C. & Erskine, R.J., 2019. Herd-level variables associated with delayed milk ejection in Michigan dairy herds. J. Dairy Sci. 102, 696-705. DOI: 10.3168/jds.2018-14561

Neijenhuis, F., Barkema, H., Hogeveen, H. & Noordhuizen, J.P.T.M., 2001. Relationship between teat-end callosity and occurrence of clinical mastitis. J. Dairy Sci. 84, 2664-2672. DOI: 10.3168/jds.S0022-0302(01)74720-0

Neijenhuis, F., Barkema, H.W., Hogeveen, H. & Noordhuizen, J.P.T.M., 2000. Classification and longitudinal examination of callused teat ends in dairy cows. J. Dairy Sci. 83, 2795-2804.

Neuheuser, A.-L., Belo, C. & Bruckmaier, R.M., 2017. Technical note: Reduced pulsation chamber vacuum at normal pulsation rate and ratio provides adequate pre-stimulation to induce oxytocin release and milk ejection while simultaneous milk flow is prevented. J. Dairy Sci. 100, 8609-8613. DOI: 10.3168/jds.2017-12937

Østerås, O. & Lund, A. 1980. The correlation between milk flow, vacuum fluctuations and decrease in vacuum in the long milk tube at the claw in different milking machines. Nord. Vet. Med. 32(8), 281-290. PMID: 7232139

Østerås, O., Rønningen, O., Sandvik, L. & Waage, S., 1995. Field studies show associations between pulsator characteristics and udder health. J. Dairy Res. 62(1), 1-13. DOI: 10.1017/S0022029900033628

Penry, J.F., Leonardi, S., Upton, J., Thompson, P.D. & Reinemann, D.J., 2016. Assessing liner performance using on-farm milk meters. J. Dairy Sci. 99, 6609-6618. DOI: 10.3168/jds.2015-10310

Penry, J.F., Crump, P.M., Ruegg, P.L. & Reinemann, D.J., 2017. Short communication: Cow- and quarter-level milking indicators and their associations with clinical mastitis in an automatic milking system. J. Dairy Sci. 100, 9267-9272. DOI: 10.3168/jds.2017-12839

Petzer, I.M. & Swan, A.C., 2018. The importance of teat liners in preserving teat integrity and udder health. RuVasa Congress Proceedings, Birchwood, Gauteng, 18-20 June, 2018.

Rasmussen, M.D. 1993. Influence of switch level of automatic cluster removers on milking performance and udder health. J. Dairy Res. 60, 287-297. DOI: 10.1017/s0022029900027631

Rasmussen, M.D. & Madsen, N.P., 2000. Effects of milkline vacuum, pulsator airline vacuum, and cluster weight on milk yield, teat condition, and udder health. J. Dairy Sci. 83, 77-84. DOI: 10.3168/jds.S0022-0302(00)74858-2

Reid, D. A. & Stewart, S.C. 1997. The effects on parlor performance by variations of detacher settings. Proceedings of 36th Annual Meeting. National Mastitis Council, Madison, WI, pp. 101-104.

Reinemann, D.J., Babe, R., Zucali, M., Spanu, C. & Ruegg, P.L., 2008. Understanding the influence of the milking machine on teat defense mechanism. Mastitis control: From Science Practice Proceedings International Conference, The Hague, Netherlands, 30 September–2 October 2008, pp 323-331.

Reinemann, D.J., 2013. Chapter 8 - Milking machines and milking parlors. In: M. Kutz (ed.). Handbook of farm, dairy, and food machinery engineering. 2nd edition. Academic Press, San Diego.

Reinemann, D.J. & Mein, G.A., 2011. Unraveling the mysteries of liner compression. Paper presented at June Countdown Meeting, Melbourne, Australia, https://milkquality.webhosting.cals.wisc.edu/wp-content/uploads/sites/212/2011/10/mysteries-of-liner.pdf; accessed June, 2022.

Reinemann, D.J. & Mein, G.A., 2018. Machine milking and mastitis risk: looking ahead, with the benefit of hindsight. Paper presented at 57th Annual Meeting of the NMC At Tucson, Arizona, USA. https://www.researchgate.net/publication/324277096; accessed June, 2022.

Reinemann, D.J., van den Borne, B.H.P., Hogeveen, H., Wiedemann, M. & Paulrud, C.O., 2021. Effects of flow-controlled vacuum on milking performance and teat condition in a rotary milking parlor. J. Dairy Sci. 104 (6). 104(6), 6820-6831. DOI: 10.3168/jds.2020-19418

Rosen, M.B., Caruolo, E.V. & Aruolo R. D. 1983. Relationship of pulsation rate, pulsation ratio, and vacuum decrease time to milking performance. J. Dairy Sci. 66 (12) 2580-2586. DOI: 10.3168/jds.S0022-0302(83)82130-4

Sandrucci, A., Tamburini, A., Bava, L. & Zucali, M., 2007. Factors affecting milk flow traits in dairy cows: Results of a field study. J. Dairy Sci. 90, 1159-1167. DOI: 10.3168/jds.S0022-0302(07)71602-8

Schukken, Y. H., Wilson, D. J., Welcome, F., Garrison-Tikofsky, L. & Gonzalez, R. N., 2003. Monitoring udder health and milk quality using somatic cell counts. Vet. Res. 34, 579-596. DOI: 10.1051/vetres:2003028

Spencer, S.B., 2011. Milking machines. Principles and design. In: J. W. (ed.) Fuquay. Encyclopedia of Dairy Sciences (second edition). Academic Press, San Diego. DOI: 10.1016/B978-0-12-374407-4.00359-9

Spencer, S.B. & Jones, L.R., 2000. Liner wall movement and vacuum measured by data acquisition. J. Dairy Sci. 83, 1110-1114. DOI: 10.3168/jds.S0022-0302(00)74976-9

Spencer, S.B., Shin, J.W., Rogers, G.W. & Cooper, J.B., 2007. Short communication: Effect of vacuum and ratio on the performance of a monoblock silicone milking liner. J. Dairy Sci. 90, 1725-1728. DOI: 10.3168/jds.2006-493

Stauffer, C., Van der Vekens, E., Stoffel, M.H., Schweizer, D. & Bruckmaier, R.M., 2021. Increased teat wall thickness in response to machine milking. J. Dairy Sci. 104 (8), 9082-9092. DOI: 10.3168/jds.2021-20294

Stewart, S., Godden, S., Rapnicki, P., Reid, D., Johnson, A. & Eicker, S., 2002. Effects of automatic cluster remover settings on average milking duration, milk flow, and milk yield. J. Dairy Sci. 85, 818-823. DOI: 10.3168/jds.S0022-0302(02)74141-6

Tančin, V., Ipema, B., Hogewerf, P. & Mačuhová, J., 2006. Sources of variation in milk flow characteristics at udder and quarter levels. J. Dairy Sci. 89, 978-988. DOI: 10.3168/jds.S0022-0302(06)72163-4

Tančin, V., Ipema, A. H. & Hogewerf, P., 2007. Interaction of somatic cell count and quarter milk flow patterns. J. Dairy Sci. 90, 2223-2228. DOI: 10.3168/jds.2006-666

Tangorra, F.M., Zaninelli, M., Costa, A., Agazzi, A. & Savoini, G., 2010. Milk electrical conductivity and mastitis status in dairy goats: Results from a pilot study. Small Ruminant Res. 90(1-3), 109-113. DOI: 10.1016/j.smallrumres.2010.02.006

Tangorra, F.M., Leonardi, S., Bronza, V. & Morani, P., 2017. Pre-milking teat stimulation and milking performance of dairy buffaloes in early lactation. J. Agri. Eng. DOI: 10.4081/jae.2017.606

Thomas, C.V., Force, D.K., Bremel, D.H. & Strasser, S. 1991. Effects of pulsation ratio, pulsation rate, and teatcup liner design on milking rate and milk production. J. Dairy Sci. 74, 1243-1249. DOI: 10.3168/jds.S0022-0302(91)78280-5

Upton, J., Penry, J.F., Rasmussen, M.D., Thompson, P.D. & Reinemann, D.J., 2016a. Effect of pulsation rest phase duration on teat end congestion. J. Dairy Sci. 99, 3958-3965. DOI: 10.3168/jds.2015-10466

Upton, J., Reinemann, D.J., Penry, J.F. & Thompson, P.D., 2016b. A quarter milking analysis device: Development and demonstration. Biosyst Eng. 147,259-264. DOI: 10.1016/j.biosystemseng.2016.04.016

Weiss, D., Weinfurtner, M. & Bruckmaier, R.M., 2004. Teat anatomy and its relationship with quarter and udder milk flow characteristics in dairy cows. J. Dairy Sci. 87, 3280-3289. DOI: 10.3168/jds.S0022-0302(04)73464-5

Wieland, M., Nydam, D.V., Älveby, N., Wood, P. & Virkler, P.D., 2018. Short communication: Teat-end shape and udder-level milking characteristics and their associations with machine milking-induced changes in teat tissue condition. J. Dairy Sci. 101, 11447-11454. DOI: 10.3168/jds.2018-15057

Wieland, M., Nydam, D.V., Heuwieser, W., Morrill, K.M., Ferlito, L., Watters, R. & Virkler, P.D., 2020. A randomized trial to study the effect of automatic cluster remover settings on milking performance, teat condition, and udder health. J. Dairy Sci. 103(4), 3668-3682. DOI: 10.3168/jds.2019-17342