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 milk 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.,...
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 (Penny 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 hyperkeratoses formation of callus-like tissue at the teat end and increases the risk of new intramammary infections (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 from 1980 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 (Penny 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 snugly 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.

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

Colours of first column indicate congestion of teats ≤3 cm long. Table colours indicate congestion of 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 & Bruckmaier 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](image)

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 prestimulation, 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-milking 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

<table>
<thead>
<tr>
<th>References</th>
<th>Number of cows</th>
<th>Duration of study, months</th>
<th>Milkings per day</th>
<th>Threshold, g/min</th>
<th>Delay time, sec</th>
<th>Machine-on time</th>
<th>Milk yield, kg</th>
<th>Teat condition</th>
<th>Udder health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rasmussen, 1993</td>
<td>135</td>
<td>36</td>
<td>2</td>
<td>200</td>
<td>18</td>
<td>NS</td>
<td>Improve</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Reid &amp; Stewart, 1997</td>
<td>-</td>
<td>3</td>
<td>400</td>
<td>12</td>
<td>-0.52**</td>
<td>Increase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stewart et al., 2002</td>
<td>3588</td>
<td>2-4</td>
<td>2</td>
<td>500-640</td>
<td>1-1</td>
<td>-0.25**</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Magliaro &amp; Kensinginger, 2005</td>
<td>60</td>
<td>12</td>
<td>2</td>
<td>600</td>
<td>-0.4**</td>
<td>NS</td>
<td></td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Jago et al., 2010</td>
<td>378</td>
<td>35</td>
<td>2</td>
<td>200</td>
<td>-0.7**</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Edwards et al., 2013</td>
<td>96</td>
<td>8</td>
<td>2</td>
<td>400</td>
<td>-0.7**</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>

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 (Tancin 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 & Ronningen, 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 milk 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 & Ronningen (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 JJK 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
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
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: 10.1017/S0295-3119(17)61893-8


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


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


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


Østerås, O., Renningen, 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/S0022029900036282


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


