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Effects of automatic cluster remover switch-point settings on milking performance and overmilking in dairy cows

MSc – Department of Production Animal studies

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Effects of automatic cluster remover switch-point settings on milking performance and overmilking in dairy cows

By

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Table of contents

Declaration

I, Pieter Vermaak declare that the dissertation, which I hereby submit for the MSc degree at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

Signature: …………………………

Date: **27/01/2021**

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List of Tables

Chapter 2:

Chapter 3:

List of Figures

Chapter 2:

Chapter 3:

List of Abbreviations

ACR - Automatic cluster remover

ATP - adenosine triphosphate

CCPD - critical collapsing pressure difference

CNS - coagulase negative staphylococci

E. coli - *Escherichia coli*

IMI - intramammary infections

ISO – International Organization of Standardization

LC - liner compression

MaxTEarly - maximum cluster attachment time from day 5 of lactation

MaxTPeak - maximum cluster attachment time

MPC – mouthpiece chamber

NAS - non-aureus staphylococci

S. aureus - *Staphylococcus aureus*

SA – South Africa

SCC – somatic cell count

SMT – short milk tube

Str. agalactiae - *Streptococcus agalactiae*

Str. uberis - *Streptococcus uberis*

TMR - total mixed rations

VaDia Biocontrol - digital vacuum recorder, (Norway)

Dissertation Abstract

The ideal milking machine harvests milk from dairy cows in a fast, effective manner without causing teat or udder damage, cow discomfort or loss in milk quality. Due to economic pressure many swing-over systems with high milk-lines were installed in South Africa, extending take-off delay with standard milking machine settings and increasing the risk of new intra-mammary infections.

The aim of the study was to investigate the effect of three automatic cluster removal (ACR) switch-point settings on machine-on time, over-milking duration, total average, peak flow- and over-milking vacuums. In a randomised trial using 65 ($n = 65$) performed on one dairy farm. Cows were selected based on their teat size, stage of lactation and udder palpation results. The trial cows were exposed for 15 milkings to each of three ACR switch-point settings (0.504 kg/min, 0.630 kg/min and 0.840 kg/min). The parlour was a 10-point, low-line, herringbone Waikato machine with the Afimilk system. Pre-milking preparations were observed while a VaDia-Biocontrol (Norway) apparatus was used to determine machine-on time and vacuums at the claw, mouthpiece and pulsator chambers during the whole milking process.

Results indicated that total machine-on time varied significantly ($p < 0.05$) between the 0.840 and 0.504 kg/min settings (290.0 to 289.2 sec) and between 0.630 and 0.504 kg/min ($p < 0.01$) (289.2 to 303.3 sec) settings respectively. Over-milking time differed significantly ($p<0.0001$) from 76.5 to 108.2 seconds between the highest and lowest volume setting. The three vacuum level measurements also differed significantly ($p<0.0001$) at each switch-point setting. Over-milking duration, as a percentage of total machine-on time, decreased from 35.7 % (at 0.504 kg/min) to 35.9 % (at 0.630 kg/min) and 26.4 % (at 0.840 kg/min) respectively.

The knowledge gained from different switch-point settings can be applied on individual dairy farms with different parlours and milking machines, to optimise settings in order to obtain a balance between milking efficiency and udder health.

Chapter 1

1.1 Introduction

1.1.1 Background

The ideal milking machine would harvest milk from dairy cows in a fast, effective manner without causing teat or udder damage, cow discomfort or loss in milk quality. A milking machine is one of the few machines connected directly to a living being on a regular basis and this needs to be taken into consideration from an animal welfare point of view. Østerås and Lund (1988) concluded that milking machine defects and faulty milking management may explain 16-45% of the inter-herd variation in udder health and that the milking machine and milking management influence udder health significantly. Although development of milking machines has excelled over the years and there has been a shift from fast milking to preservation of the teat canal and longevity of the cow, it still causes challenges to udder health. High milk production increases the culling risk, mostly for multiparous cows early in lactation, mainly due to poor udder health (Gussmann *et al*., 2019). According to Lactodata (2013 and 2018), production in commercial dairy cows in South Africa showed a linear upward trend over time with a production of 17.3 kg/day in the 2007 to 20.0 kg/day in 2017**.** A survey completed in 2016 by Lactodata (2018) found the average herd sizes in South Africa to be 354 cows at that time.

1.1.1.1 Longevity in dairy cattle

Longevity and functional traits (fertility, health and conformation) have become a focus in dairy cattle breeding goals throughout the world (Clasen *et al*., 2017). Clasen *et al*., (2017) described longevity as a complex trait that is affected by production traits, functional traits and other factors such as management or the farmers' decisions. The most common pure dairy breed in South Africa is Holstein cows. According to Gabriela *et al*, (2018) their extreme milk yields are associated with shorter longevity. In a Swedish study the overall most common reason (26.7%) for culling in Swedish organic herds was poor udder health based on mastitis cases and high somatic cell counts (Ahlman *et al*., 2011). There are many factors that may affect udder health. Therefore, more emphasis is placed on herd-specific advice to improve udder health (Rajala-Schultz *et al*., 2019).

1.1.1.2 Preservation of the teat canal

Preservation of the teat canal and support of the immune system of the udder to assist in the control of new intramammary infections (IMI) and the risks thereof, are required in order to maintain good udder health. Udder hygiene should be assessed at milking because it influences milk quality and is related to the occurrence of pathogens, especially those of environmental origin (De Pinho Manzi *et al*., 2012). A study conducted by De Pinho Manzi *et al*. (2012) concluded that animals with very rough teat end rings and dirty udders have a greater predisposition to IMI. An increase in teat-end condition and udder hygiene scores increased the risk of IMI by 30% and 47% respectively (De Pinho Manzi *et al*., 2012).

1.1.1.3 Milking machine and milking performance

There are many factors associated with the milking machine that can damage the teat canal of the cow. Milking machine defects may have detrimental effects on udder health as it increases the risk of IMI (Østerås and Lund, 1988). Milking machines may cause bacteria to be pushed from the exterior into the teat sinus and thus play a major role in the incidence of mastitis (Neijenhuis, 2011). According to Rasmussen and Madsen (2000), system vacuum may play a major role in the change of teat condition and cause bacteria to penetrate the teat canal. A holistic approach towards milking is essential, which includes the machine, its' components (i.e., teat liners), settings, maintenance, parlour hygiene, management, the immune system of the cow and the challenge of micro-organisms.

Milking performance can be affected by the milking machine when changing the pulsation ratio, pulsation rate and vacuum (Rosen *et al*., 1983). With the growth of the dairy industry, the milking facility has become more central to the dairy operation. Besides the land, it is one of the largest capital investments and a big part of the operational costs of a dairy (Thomas *et al*., 1993). The interaction of liner characteristics with the milking machine settings are important as this will affect milking duration, peak flow and average flow rate. Spencer *et al*. (2007) found that there was significant difference ($p<0.05$) between milking duration, peak flow rate and average flow rate between a vacuum of 43.9kPa and pulsation ratio 65:35 as a result of the liner.

The vacuum level at teat end is affected by a number of factors such as the milking vacuum, length of the B phase of the pulsator, take-off timing and milk yield of the cow. During machine milking, milk is removed from the teat cisterns under vacuum. Different levels of claw vacuum during milking may affect milking performance and teat condition (Besier and Bruckmaier, 2016). Neijenhuis (2011) suggested that milking vacuum levels of 40-46 kPa should be used for low milk-lines and 47-50 kPa for high milk-lines, to ensure that the vacuum does not exceed 40-42 kPa at the teat end during peak milk flow. The milking machine induces short-term changes such as teat end callosity and teat thickness which are linked to the weakening of the teats' defence mechanism making them more susceptible to IMI (Niejenhuis *et al*., 2001). The results of the study completed by Wieland *et al*. (2017) support the idea of decreased machine-on time, as with previous studies (Besier and Bruckmaier, 2016; Erskine *et al*., 2019; Rasmussen, 1993; Sagi, 1978), in which overmilking is decreased and ACR settings are increased, in order to improve teat tissue condition.

1.1.1.4 Parlour layout and milking machine installation

Milkline height selection criteria in a milking parlour relates to the cost of installation, organisation and efficiency of milking, all of which may have possible effects on udder health (Díaz *et al*., 2004). With the current situation in South Africa, economic pressures tend to lead to the installation of many swing-over dairy parlours with high milklines in order to reduce installation costs. The advantages of the installation of a high milk-line, mid milk-line or low milk-line may depend on the desired end result, i.e., milking efficiency or reduced installation costs (Díaz *et al*., 2004). With increased labour costs and work pressure due to the increase of herd size, ACRs are being installed in many of these swing-over parlours. Due to the distance from the teat end to the flow meter in such parlours, take-off time may be unduly delayed and overmilking is likely to occur at the end of milking.

1.1.1.5 Overmilking and automated cluster removal

Overmilking starts when the milk flow to the teat cistern is less than that of the flow to the teat canal (Rasmussen, 2004). Overmilking can be caused by periods of extended milking during low milk flow because of incorrect ACR settings, removal of clusters by milking personnel or re-attaching the clusters after milking (Rasmussen, 2004). Overmilking may lead to teat congestion and can either occur at the start of milking prior to milk let down, during milking or at the end of milking when clusters remain on for too long. In a study by Moore-Foster (2019), it was concluded that for milking facilities running below maximum capacity, variables such as equipment function or manual cluster removal are the most important risk factors for overmilking. Digital vacuum recorders were used to determine herd-level variables that are associated with overmilking (Moore-Foster, 2019).

Automatic take-off settings detect a low milk flow from the teat end and initiate the milking cluster to detach from the udder, whether the cow is fully milked out in all 4 quarters or not. This action prevents overmilking and helps to maintain teat end condition (Nickerson and Oliver, 2014). Healthy teat canals and teat orifices are less prone to bacterial colonisation and subsequent development of IMI.

1.2 Justification

The integrity of the teat canal of the modern-day cow is increasingly challenged while milking by machine. One of the most important criteria is the vacuum level at teat end during milking. At the end of milking, milk flow decreases and the vacuum level at the teat end increases. When milking continuous with little or no milk being removed from the quarter, the quarter will be subjected to tissue stress (Ginsberg *et al*., 2018). Overmilking is an undesirable condition of extended periods of milking, leading to the deterioration of condition of the teat end (Hillerton *et al*., 2002).

Natzke *et al*. (1978), already stated in early years that overmilked quarters had severe injury to the internal teat structure where pathological changes included hyperemia, hemorrhage and oedema of the epithelial membrane. The duration of milking can be altered by changing the end-of-milking flow setting for the ACR (Magliaro and Kensinger, 2005). Limited information is available on the effective milk flow and teat end vacuum at the end of milking. According to Ginsberg *et al*. (2018) on-farm adjustments of ACR factory default settings will significantly improve teat condition and parlour throughput.

1.3 Aim

The aim of this study was to compare the effect of three ACR switch-point settings on overmilking duration and vacuum level and milking duration.

1.4 Objectives

1. To investigate the effect of three ACR switch-point settings on overmilking duration and vacuum level during overmilking in relation to the total system vacuum.
2. To determine milking duration and vacuum at the different ACR switch-point settings.

1.5 The benefits of the study

This research will provide insight into efficiency of take-off settings in milking systems and will be able to be applied in practice by commercial dairies, mainly those with swing-over parlour layouts utilizing ACR. Correct ACR take-off settings may assist to maintain teat canal integrity and the primary immune system of the udder and in so doing assist with prevention of mastitis and increase longevity of cows. Milking equipment suppliers, dairy farm advisors and operators can use this advice to improve milking performance and quality. This work can assist in the set unique and tailor made per farm ARC switch-point settings to ensure milking efficiency addressing udder health, cow comfort and milking duration.

1.6 Structure of the dissertation

This dissertation comprises of four chapters. The first chapter provides the general background, aim, objectives and structure of the dissertation. The second chapter is a literature review which outlines published studies on the effect of system vacuum and ACR switch-point settings on udder health and milking efficiency. The third chapter provides information on the current study, its' methodology, indicates the results obtained and summarises the findings, which will be submitted to a scientific journal for publication. The last chapter summarises the findings of the dissertation and the importance thereof.

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Chapter 2

2.1 Introduction to mastitis

2.1.1 The dairy situation in South Africa

The farming situation in South Africa has changed significantly over the past 15 years. The average herd size in South Africa is 354 cows second only to New Zealand and Saudi Arabia. Approximately 48% of the South African herds had more than 300 cows (Lactodata, 2019) with a mean daily milk yield of 21.0 kg in 2018. South Africa has two farming systems, total mixed rations (TMR) and pasture-based feeding. The number of bovine dairy producers in South Africa decreased by 65% from 3 551 in January 2009 to 1 253 in January 2019, while milk production increased by 31% and milk production per producer by 273% for the same time period (Lactodata, 2019). The average yearly production in 2017 was 3.3 million tons worth 16.54 billion ZAR (Lactodata, 2018).

Many South African dairy parlours have swing-over systems where a high milkline is situated in the center above the milking pit and milking units are used alternatively between cows on both sides of the pit. Due to the drastic increase in cow numbers per herd more producers have had automated cluster removals (ACR) installed. In the swing-over parlour the flowmeter can only be installed 2.5 to 3 meters away from and above the cow's udder. This will increase the delay time of ACR activation, which could lead to an increased risk of overmilking and its' consequences due to late take-off (Petzer and Swan 2018).

2.1.2 Economics of bovine mastitis

Bovine mastitis is an important disease globally and the most costly disease of dairy cattle in first world countries (Halasa *et al*., 2007). According to Giesecke *et al*. (1994) subclinical mastitis is responsible for more than 80% of monetary losses. Losses are mainly due to reduced milk quality and quantity following subclinical mastitis (Halasa *et al*., 2007; Hogan *et al*., 2016). Farmers often underestimate the cost associated with mastitis (Huijps *et al*., 2008), as they only account for direct costs and losses. Direct costs include veterinary costs and medication, discarded milk and decreased milk quality (decreased lipolysis index) (Hortet and Seegers, 1998). Indirect costs and long-term losses are more difficult to calculate (Heikkilä *et al*. 2012). These include milk production loss especially during the remainder of lactation due to udder damage or premature drying-off, lower life production, increased culling, increased replacements, loss in genetic potential, increase in labour costs and penalties for inferior milk quality (Hortet and Seegers, 1998).

Although the mortality rate for clinical mastitis is low (Seegers *et al*., 2003), it meaningfully increases the risk of culling (Bar *et al*., 2008). Culling is an important tool in dairy herds to make room for younger animals with higher genetic merit (Gussmann *et al*., 2019), but it also influences longevity. In recent years lower culling rates are often viewed as favourable as it affects the cost and environmental effects of herd sizes. Health traits have a low heritability and because of this negative correlation, cows with high production have a higher risk of contracting mastitis (Ouweltjes *et al*., 2007). Due to the high economic value of longevity in dairy cows (van der Beek, 1999), the major reasons for culling that include mastitis, should be managed in such a way as to lower the risk (Beaudeau *et al*., 1993).

The way in which economic losses of mastitis are calculated differs greatly amongst researchers. Studies, that assess production loss within the cow by comparison of production before and after infection, tend to estimate the loss incorrectly because of the effect of lactation stage on the animal-specific lactation curve as explained by Rajala-Schultz *et al*. (1999). Hortet and Seegers (1998) estimated that production loss due to subclinical mastitis displayed low precision of the estimated loss. Halasa *et al*. (2009) used a random regression test-day modelling method to estimate the effects of disease on production, which showed a significant loss in milk, fat and protein production of dairy cows with subclinical mastitis. According to Rollin *et al*. (2015) an average case of clinical mastitis can cost up to 444 U.S Dollar (USD), of which128 USD are direct and 316 USD indirect costs. Mastitis was estimated to cost the United States close to 2 billion USD in 1993 (Petrovski *et al*., 2006). The long-term indirect cost due to mastitis, can represent up to 70% of the total cost per clinical case and 30% of the total cost in future loss of milk production (Rollin *et al*., 2015).

2.1.3 Clinical mastitis

Since the beginning of modern dairy farming, producers have sought effective methods to minimize the occurrence of mastitis in their herds (Ruegg, 2017). Mastitis, an inflammation of the mammary gland, is characterised as the most common infectious disease affecting dairy cattle (de Pinho Manzi *et al*., 2012). Bacteria invade the teat canal and mammary glands, where they multiply and produce toxins that cause injury to the milk secreting tissue, besides physical trauma and chemical irritants (Khan and Khan, 2006). When potentially pathogenic organisms penetrate the teat canal and enter the teat cistern, the outcome will depend on the number of organisms introduced, the virulence of the pathogen, time of entry relative to milking and the efficiency of the animal's immune mechanism to overcome the infection. The severity and outcome of intramammary infection (IMI) infection is also dependent on several host factors including innate host resistance, energy balance, immune status, parity and stage of lactation (Keane, 2019).

Somatic cell count (SCC) is recognised as an indicator of udder health and milk quality and is the most frequently used indicator of subclinical mastitis in dairy cattle (de Pinho Manzi *et al*., 2012; Tsenkova *et al*., 2001). The most important cause of increased SCC is bacterial infection of the mammary gland (De Haas *et al*., 2004; Olde Riekerink *et al*., 2007; Tsenkova *et al*., 2001). Although SCC is a cost effective and fast laboratory measurement, it provides only an indication of probable IMI and does not predict IMI accurately at the 200 000 cells/ml milk quarter threshold or 150 000 cells/ml milk composite cow milk threshold (Petzer *et al*., 2016). According to Shearer and Harris (2003), subclinical mastitis is 15 to 40 times more prevalent than the clinical form which it precedes, is of longer duration and more difficult to detect. It adversely affects milk quality and production and constitutes a reservoir of micro-organisms that lead to infection of other animals within the herd. Bulk milk SCC in a herd is mainly influenced by the prevalence and incidence of subclinical and clinical mastitis. This depends on factors such as parity, stage of lactation, type of housing, access to pasture, management and environmental factors such as extreme temperature, humidity and season (Faye *et al*., 1998; Hogan and Smith, 1997; Morse *et al*., 1988; Riekerink *et al*., 2007; Simensen, 1976). Many European countries, Australia and New Zealand set their allowed maximum bulk milk SCC for human consumption at 400 000 cells/ml milk, while it is 500 000 cells/ml milk in South Africa and Canada and 750 000 cells/ml milk in the USA (Department of Health 1997, Olechnowicz, 2012, Schukken *et al*., 2003).

2.1.4 Mastitis pathogens

The distribution of pathogens isolated from clinical mastitis samples differs considerably among countries and even among studies within a country (Olde Riekerink *et al*., 2008). Zadoks and Fitzpatrick (2009) reported that there have been changes in the relative proportion of mastitis pathogens in first world countries due to changes in herd and parlour management, udder health monitoring, treatment and differences in genetics. Knowledge of mastitis pathogens remains important as the categorisation thereof reflects the basic epidemiology and aids in pro-active management (Petzer *et al*., 2009).A study by Petzer *et al*. (2009) found that most cases of subclinical mastitis in South Africa have been caused by: Non-aureus staphylococci (NAS), *Staphylococcus aureus*, *Streptococcus agalactiae* and *Streptococcus uberis*. Non-aureus staphylococci, previously regarded as minor pathogens, are now causing an increasing number of clinical mastitis cases and increasingly high SCC (Petzer *et al*., 2009; Zadoks and Watt 2009).

Zadoks and Fitzpatrick (2009) found only a few species of Staphylococci, Streptococci and Gram-negative organisms that are currently considered to be of economic importance. Ruegg (2017) found that the most important contagious bacteria that reach the mammary gland through the teat canal are *Streptococcus agalactiae*, *Staphylococcus aureus* and mycoplasma species. Infectious bacteria can be grouped as major or minor mastitis bacteria, based on their effect on udder health. Vanderhaeghen *et al*. (2015), classified major pathogens as *Staphylococcus aureus*, *Escherichia coli (E. coli*), *Streptococcus agalactiae* and *Streptococcus uberis* and minor pathogens as *Corynebacterium* spp. and NAS.

Non aureus staphylococci formally called coagulase negative staphylococci (CNS) have become the microorganisms most frequently isolated in subclinical mastitis samples in many countries (De Vliegher *et al*., 2012; Schukken *et al*., 2009; Supré *et al*., 2011; Vanderhaeghen *et al*., 2015). Early studies consider NAS as minor mastitis pathogens whereas later studies regard them as major pathogens (Schukken *et al*., 2009; Supré *et al*., 2011; Vanderhaeghen *et al*., 2014). More than 53 species of NAS have been classified but NAS has been regarded as a homogenous group (Vanderhaeghen *et al*., 2015). On many well managed dairy farms, where contagious bacteria are controlled or eradicated, NAS has become the foremost cause of subclinical mastitis (Schukken *et al*., 2009). There have been conflicting results on aspects such as the effect which NAS IMI have on SCC and milk yield, as this is dependent on the specific species of NAS. There are also different results on their potential virulence and epidemiology causing confusion regarding the true importance of NAS bacteria for udder health (Vanderhaeghen *et al*., 2014). According to Supré *et al*. (2011) the importance of NAS and the conflicting findings can be attained mostly to identification issues.

2.1.4.1 The role of mastitis causing bacteria

Microorganisms such as bacteria, mycoplasmas, yeasts, algae and on rare occasions, viruses can cause IMI with bacteria being the most common (Nickerson, 2011). Mastitis causing bacteria are divided into primary environmental or contagious (host adaptive) organisms (Coffey *et al*., 2006; Schreiner and Ruegg, 2002). Milking machines have been concluded to be of lesser importance when looking at the spread of pathogenic bacteria compared to other management factors, especially if the milking machine functions correctly. They do, however, still pose a potential risk for the spread of pathogenic bacteria by acting as a fomite for the transportation of infected milk and or bacteria from lesions on the teat on the teat cup liner and exposing the teat ends of other cows that are milked with the same liners (Malmo *et al*., 2010). Non-infected quarters are at risk when changes in vacuum force droplets of infected milk from the teat end into the teat canal. When the milking machine causes physical damage to the teat end, the physical barrier that is formed by the teat canal loses its effectiveness to protect the udder from bacteria (Malmo *et al*., 2010).

Contagious bacteria may spread through many vectors mainly people, milking machines and flies, between infected and uninfected quarters (Oliver *et al*., 2011; Vanderhaeghen *et al*., 2015). For a long time, *Streptococcus agalactiae* and *Staphylococcus aureus* were noted to be the most important contagious pathogens (Khan and Khan, 2006; Ruegg, 2017). *Mycoplasma bovis*, which doesn't have a cell wall, is also an important contagious bacterium (Nickerson, 2011). Lesions in the teat sphincter are often colonised by staphylococcus spp. and streptococcus spp. (Neijenhuis *et al*., 2000) this shows that there is a link between the physical condition of mammary quarters and the presence of micro-organisms**.**

Environmental micro-organisms are mostly non-contagious pathogens. Mastitis caused by environmental bacteria differs noticeably in epidemiology compared to that of contagious bacteria and comprises of a heterogenous group of bacterial genera and species (Oliver *et al*., 2011). These organisms can spread from infected quarters to uninfected quarters during the milking process, although it is mainly due to contamination from the surrounding environment. Environmental pathogens originate from the cow's own environment, especially when housing conditions are sub-optimal (Vanderhaeghen *et al*., 2015). Environmental pathogens do not colonise on the teat surface, in the teat canal or in teat lesions and therefore the udder is not a primary source of infection. Environmental pathogens are commonly found in faeces, genital discharge, bedding, feedstuffs, soil and water. If manure, bedding and other contaminants are not removed at each milking, the bacterial load at the teat end is increased (Oliver *et al*., 2011). Prolonged and close contact of particularly the teat end with the environmental contaminants are most common in the calving area, milking area, milking shed and dry cow area.

Gram-negative coliforms and environmental streptococci are the two main environmental groups. Depending on management and risk the most prominent environmental bacteria isolated, differ between herds. Oliver *et al*. (2011) insolated *Streptococcus uberis*, *Streptococcus dysgalactiae*, *E. coli* and Klebsiella species most frequently, whereas de Pinho Manzi *et al*. (2012) found coliform bacteria and environmental streptococci to be the most isolated environmental pathogens.

2.1.4.2 Teat congestion

One papillary artery supplies the teat with blood while a superficial network of smaller arteries supplies the teat skin. The veins situated in the teats are large and have thick walls with numerous valves directed towards the teat base (Konig and Liebich, 2009).

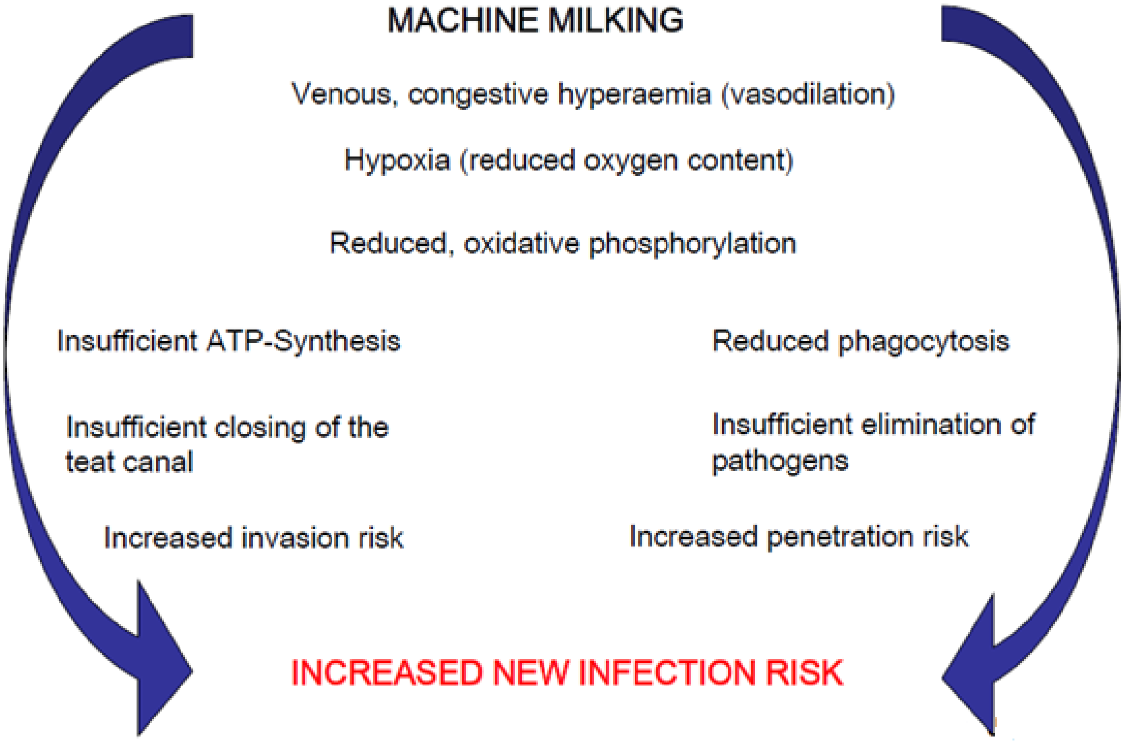

Figure 2.1: Adapted by Rasmussen (2017) from Hamann, (1991)

Congestion is the accumulation of blood within the circulatory system. Congestion takes place in the venous system of the teats causing vasodilatation followed by hypoxia and reduced oxidative phosphorylation. Less nutrients are available to oxidize and less energy is released for production of adenosine triphosphate (ATP). With less ATP available the closure of the teat canal may be impaired (Hamann *et al*., 1991). Reduced oxidative phosphorylation reduces the ability of the polymorpho-leucocytes to phagocytise. Insufficient ATP-synthesis, reduced phagocytosis and inefficient elimination of pathogens are factors that lead to a higher risk of new infections. The teat should be inspected for changes such as congestion, discoloration and teat canal damage (Ohnstad and Reinemann, 2017). During the early stages of oedema there is only transudation of water and low molecular weight substances into the interstitial tissue. Later the high molecular weight substances may leave the capillaries by exudation.

The extent and persistence of congestion and oedema will depend on the milking conditions and milking duration (Hamann and Mein, 2009). According to Hamann and Mein (2009) machine milking induced repeatable short-term changes in thickness of the teat apex. Hamann and Mein (2009) studied machine-induced changes in thickness of the bovine teat using a spring-loaded caliper and concluded that changes in the teat end thickness varied depending on the type of milking system used. Hamann and Mein (1988) investigated the thickness of the teat end in response to different vacuum settings (30kPa, 50kPa, and 70kPa) and found that the teat-end thickness and tissue stiffness increased as the vacuum level increased. Thirty minutes after milking at 50 kPa, teats were still congested (Hamann *et al*., 1993). The vacuum level at the teat end and/or liner mouthpiece may lead to congestion of the teat end, which depends on liner fit and vacuum level (Hamann, 1993).

Milking at a higher milking vacuum resulted in more colour changes of the teat, cracks in the epithelium of the teat tissue and increased keratinisation of the teat orifice (Besier and Bruckmaier 2016; Ebendorff and Ziesack, 1991). During higher milking vacuum it was found that teats increased in length, teat diameters decreased at the base and the middle increased in width at the teat end, while the teat wall became thicker. Upton (2017) indicated a 20% difference in formation of teat congestion between gentle and aggressive milking.

2.2 Immune system of the bovine udder

According to Sordillo *et al*. (1997) the defence of the mammary gland against mastitis-causing pathogens is mediated by several anatomical, cellular and soluble protective factors. In early lactation the mammary defences often fail to function correctly and cows become more vulnerable to mastitis (Sordillo *et al*., 1997). Individual components of the mammary immune system can be generally classified into different functional categories that include the innate and adaptive (or acquired) immune responses (Sordillo, 2018).

2.2.1 Primary udder defense

The teat canal is considered to be the first line of defense against mastitis or invading pathogens and the primary defense mechanism of the udder (Khan and Khan, 2006). Mammary quarter level risk factors for IMI may include teat position and shape (Breen *et al*., 2009). The teat sphincter and teat canal are important primary barriers against pathogen invasion into the udder (de Pinho Manzi *et al*., 2012). The teat end contains sphincter muscles that maintain tight closure between milkings and hinder bacterial penetration (Sordillo *et al*., 1997). Once the teat canal is damaged or dilated after milking, the risk of ascending infection increases (Kehrli and Harp, 2001). The canal of a teat may remain partially open for 1-2 hours after milking and during this period the pathogens may freely enter the teat canal (Jones, 2006; Viguier *et al*., 2009). A study done by de Pinho Manzi *et al*., (2012) to relate IMI occurrence and SCC with teat-end condition and udder condition, concluded that teat ends with very rough keratin rings extending more than 4 mm from the orifice and had the highest chance of developing IMI when compared to the other categories, as well as animals with dirty udders.

The teat canal is lined with keratin derived from stratified squamous epithelium (Khan and Khan, 2006). Keratin obstructs the migration of bacteria and contains antimicrobial agents, such as long-chain fatty acids that assist in combating infection (Khan and Khan, 2006; Sordillo *et al*., 1997; Viguier *et al*., 2009). These esterified and non-esterified fatty acids present in teat keratin, such as myristic acid, palmitoleic acid and linoleic acid, are bacteriostatic in action (Treece *et al*., 1966). Additionally, cationic protein in the canal can bind electrostatically to mastitis pathogens, which alters the bacterial cell wall, thus rendering them more susceptible to osmotic pressure (Sordillo *et al*., 1997). The fibrous proteins of keratin in the teat canal bind electrostatically to mastitis pathogens, which alter the bacterial cell wall to cause the inability of the cell to maintain osmotic pressure that causes lysis and death of invading pathogens (Treece *et al*., 1966). According to Viguier *et al*. (2009) the efficiency of keratin is restricted when fluid accumulates within the mammary gland as parturition approaches, resulting in increased intramammary pressure and mammary gland vulnerability caused by the dilation of the teat canal and additionally during milking the keratin is flushed out. Increased patency or dilation of this opening increases the incidence of mastitis (Khan and Khan, 2006). Damage to keratin has been reported to increase the susceptibility of the teat canal to bacterial invasion and colonisation (Bramley and Dodd, 1984).

Lymphocytes and plasma cells accumulate beneath and between the epithelial cells of the teat canal and particularly at Fürstenberg’s rosette to deal with bacteria that have gained entrance (Sordillo *et al*., 1988a; Sordillo *et al*., 1988b). Epithelial desquamation and continued milk flow during lactation helps to prevent bacterial colonisation in the teat canal. Most IMI are due to the ability of pathogens to overcome the anatomical physical barrier of the teat canal (Wellnitz and Bruckmaier, 2012). Once the pathogens have passed through the teat canal, the mammary gland’s secondary (innate and adaptive) immune responses are triggered.

2.2.2 Secondary udder defense- Innate and adaptive immunity

Innate immunity refers to a set of non-specific resistance mechanisms that can be activated within seconds to minutes of the bacterial invasion (Sordillo, 2018). These mechanisms are a combination of chemical secretions (lactoperoxidases, lactoferrin and complement) and a cellular immune response (macrophages, neutrophil and natural killer like cells) (Kehrli and Harp, 2001; Tizard, 2013). As stated by Wellnitz and Bruckmaier (2012), interaction between both polymorph nuclear (PMN) leukocytes in the milk and the udder epithelial cells with pathogens invading the udder, activates the innate immune system. This is done through the transcriptional activation of fundamental response genes. Although innate immune responses are characterised as non-specific, it is only established when specific pattern recognition receptors on the surfaces or within host cells bind with distinct bacterial molecules termed pathogen-associated molecular patterns (PAMP). The pattern recognition receptors are expressed on leukocytes found within milk and on the epithelial cells that are lining in the mammary gland (Goldammer *et al*., 2004; Strandberg *et al*., 2005; Wellnitz and Bruckmaier, 2012). A swift and sufficient innate immune response is based on early recognition of potential pathogens (Akira *et al*., 2006). When the innate immune response fails to clear the bacteria, the latter multiply once inside the teat cistern and become vested in the mammary parenchyma (Rainard and Riollet, 2006).

The innate immunity follows being a response of the adaptive immune system (Tizard, 2013). The adaptive immune system relies on antigen specific T and B lymphocytes for an antibody-mediated response as well as a cell-mediated response against intracellular pathogens (Tizard, 2013). This recruitment of cells means that the adaptive immunity takes longer to develop after microbial exposure compared to the innate immunity. The innate immunity has a limited number of preformed receptors that bind to molecules expressed by different pathogens (Tizard, 2013). Whereas adaptive immunity can generate enormous amounts of unique receptors specific to the foreign molecules that induce them (Tizard, 2013).

2.3 Parlour layout

A milking parlour is a tool to implement proper and consistent milking techniques with improved efficiency, safety and a comfortable working space for milking personnel (Reinemann and Rasmussen, 2011). There are different parlour layouts each with their strengths and weaknesses. A herringbone parlour has a relative low capital outlay and running cost but milking duration is prolonged, particularly if there is significant variation in yield within a group of cows being milked. Swing-over parlours can be used on herringbone or parallel parlours and this configuration reduces the number of milking units to reduce the initial cost of construction (Reinemann and Rasmussen, 2011). With rapid exit parlours capital costs may be higher as they contain more moving parts for maintenance. Rapid exit systems can achieve high throughputs with good working environments for the operator. However, these require high capital outlay and maintenance costs, which may be difficult to provide individual cow attention with the moving table. Rotary parlours may range from 4 to 5 turns per hour with 2 to 4 operators, depending on the number of stalls (Reinemann and Rasmussen, 2011).

2.3.1 Parlour layout affects milking machine settings

The ISO 5707:2007 (Milking machine installations – Construction and performance) guide for milking machine installations, construction and performance, stipulates that a milking system with a milk-line at 1.26m or more above the standing animal is identified as a highline milking system, when 1.25m or less above the standing animal is identified as a midline, while a system with the milk-line below the position of the standing animal is identified as a low line milking system. The installation of high or midlines compared to low milk-lines, have lower installation costs and greater efficiency in milking for the same number of operators (Díaz, *et al*., 2004). Alternatively, a low milk-line system allows milking to occur at a lower vacuum level without impacting on the rate of liner slip (Fernández *et al*., 1997) and this can maintain a more stable teat end vacuum (Østerås and Lund, 1980). Advances in milking machines' development have greatly improved vacuum stability (Ruegg, 2018).It is important to slope milklines towards the receiving jar, as increasing the slope increases the carrying capacity of the milklines (Reinemann and Rasmussen, 2011).However, the ISO guidelines state that the milkline and internal diameter should be installed in such a way that the vacuum drop between the receiver and any other point in the milkline should not be more than 2 kPa, allowing all units to function according to design (ISO 5707:2007).The length of the milk pipe and number of fittings should be kept to a minimum to reduce installation cost and to improve milking and washing performance (Reinemann and Rasmussen, 2011).

A review of different levels of claw vacuums completed by Besier *et al*. (2016), stated that vacuum drop depends on the technical characteristics of the milking system and increases with increased milk flow rate. The highest vacuum drop occurs in high milk-line milking systems at high milk flow rates. The main exposure of the teat to high claw vacuum occurs towards the end of milking when milk flow declines or ceases sequentially in individual quarters, while vacuum at teat end increases gradually. At the end of milking when milk flow has declined, high milking vacuum translates into high teat end vacuum (Isaksson and Lind, 1992). Teat congestion is caused by the development of high vacuum in the mouthpiece chamber of the liner (Ginsberg *et al*., 2018).

2.4 Parlour management

For decades, researchers have evaluated associations between milk harvesting indicators and occurrence of clinical and subclinical mastitis (Dodd *et al*., 1969; Penry *et al*., 2017). Powerful physical forces are applied by the milking machine to a cow's teats for 4 to 10 minutes, 2 or 3 times every day and milking machine effects may account for up to 20% of new infections in some herds provided the machine settings are correct (Rasmussen, 1994; Schukken, 2003).Control depends on many factors which have been found to influence the incidence of disease. 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, effective cleaning of milking units after milking a mastitis cow, timely unit adjustment, proper alignment and optimal nutrition (including trace elements) (Rasmussen, 1994; Schukken, 2003). These effects may directly increase the new IMI rate or indirectly increase exposure to bacteria or reduce disease resistance. Mastitis risk is reduced by keeping bacterial numbers on the teat-ends low, especially if machine settings and/or milking management practices are less than ideal (Mein, 2012).

2.4.1 Milk let-down stimulation

Milk is stored in the cistern and the alveolar tissue. The contribution of alveolar milk to total milk in the udder decreases with milking intervals, stage of lactation and parity. After a 12-hour milking interval the alveolar contains approximately 80% of the total milk fraction (Sandrucci *et al.,* 2007). The milk in the cistern can be removed by overcoming the barrier of the teat sphincter while the milk in the alveolar has to be moved actively to the cistern via the milk ejection reflex (Sandrucci *et al*., 2007). Teat stimulation activates a neuroendocrine mechanism resulting in oxytocin release that causes contraction of myoepithelial cells surrounding the alveoli and ejection of alveolar milk (Bruckmaier and Blum, 1996). Oxytocin is required for myoepithelial contraction to induce alveolar milk ejection in dairy cows and tactile stimulation of the udder is therefore essential (Bruckmaier and Blum, 1996; Bruckmaier, 2005). Stressful situations, inconsistent milking routine, poor cow handling, sick cows (lameness, mastitis and systemic diseases), incorrect machine settings and stray voltage can inhibit the let-down reflex or prevent it from occurring.

Without pre-stimulation, the milk reflex is delayed. This happens when clusters are attached without any prior stimulation resulting in a transiently reduced milk flow, after the milk in the cistern is removed and prior to alveolar milk ejection. This bimodal milk flow is the result of interrupted milk flow prior to the oxytocin induced alveolar milk flow (Bruckmaier and Blum, 1996; Sandrucci *et al*., 2007). Bimodality may have negative effects on milking efficiency, cause an extension of machine-on time and challenge teat and udder health due to effects that are similar to overmilking (Bruckmaier *et al*., 1995; Bruckmaier *et al*., 1996; Sandrucci *et al*., 2007). Rasmussen *et al*. (1992) suggested an optimal pre-stimulation of 20 to 30 seconds associated with a delay of 1.3 minutes from the beginning of preparation to machine attachment, while Bruckmaier and Hilger (2001) suggested a 1 to 2minutedelay depending on the degree of udder filling. According to Sandrucci *et al*. (2007) the duration of the delay between initiation of udder preparation and cluster attachment affects the milking time substantially. Erskine *et al*. (2019) found a negative correlation between delayed milk ejection and milk yield.

The milk let-down reflex, that increases the pressure within the udder is most effective during the first 3 minutes but is fully functional for 5 minutes. Herds with high daily milk yields may have average milking times exceeding 5 minutes. In these herds parlour management needs to utilise the full let-down reflex to prevent overmilking and undermilking (Petzer *et al*, 2016). Over the years, the production levels of cows have dramatically increased, leading to increased average milk flow rates. The modern commercial Holstein cow is now dried off when she is producing a similar volume that a cow in 1975 produced at her peak lactation (Cole *et al*., 2017).

2.4.2 Liner slip

Vacuum is the main force keeping the teat liner on the teats during milking. When the milking vacuum lowers, liner slips may increase. Liner slips can occur when conditions lead to a sudden, transient inrush of air through the liners. When milking at a low milking vacuum the machine-on time and frequency of liner slip increases (Rasmussen and Madsen, 2000; Spencer, 2011). Rasmussen and Madsen (2000) recommended that the mean vacuum in the short milk tube at peak milk flow should not be lower than 32kPa. According to Baxter *et al*. (1992) liner slip and the risk of new IMI increased when cows were milked with the high slip liners compared to low slip liners with a shallow mouthpiece. High slip liners allow for sudden air admission between the liner mouthpiece and the bovine teat skin. Spencer (2011) found that liner slips are influenced by udder shape, teat location, cluster alignment, teat preparation into liners, liner design and liner fit. When liners with a bore which is too wide are used, the ability of the teat to elongate is reduced. The teat will be shorter during milking than when milked with a liner that fits, causing the b-phase to be less effective. This may lead to reduced liners' slip but increased teat congestion.

2.4.3 Cluster alignment

There are cases where faulty equipment or malfunctioning of the milking machine may lead to inadequate milk removal. Penry *et al*. (2017) concluded that an immediate and significant decrease in milk production rate is observed in quarters that are milked incompletely compared to udders that are milked out completely. Incomplete milking tends to increase the new infection rate or may even cause subclinical mastitis to progress to clinical mastitis (Neijenhuis, 2011). In contrast, milking regimes leaving behind an average of 0.5kg strip milk did not seem to increase the SCC in infected or uninfected quarters (Wieland *et al*., 2020). In this case mismatch of the claw inlet and the short milk tube or cluster alignment may be perpetuating factors. Good cluster alignment improves completeness of milking and affects the precision of the ACR in order to determine the end of the milk flow (Ginsberg *et al*., 2018).

2.4.4 Cluster detachment

The correct detachment of cluster units is important to udder health as the teat is the boundary between the teat cup liner and the mammary gland (Stauffer *et al*., 2020). During overmilking claw vacuum generally increases and fluctuations become larger (Ginsberg *et al*., 2018). Under no circumstances should a cluster be forcefully removed when there is still vacuum present. Measurements at the teat indicate immediate changes in milk flow from the udder, while measurements of the milk flow in the milk flow meters are delayed to a more or lesser degree depending on the distance and height of the meter in relation to the udder of the cow (Ginsberg *et al*., 2018). To determine overmilking, flow from individual quarters should thus be measured close to the teat.

Machine milking causes the teat to be stretched to 40 % during milking (Thiel and Mein, 1977) in length as well as sideways when liners do not fit snuggly. Excessive stretching of the teat, mainly towards the end of milking, may increase teat oedema and in time teat end hyperkeratosis (Hamann *et al*., 1994; Neijenhuis *et al*., 2000).

2.4.5 Overmilking

Overmilking occurs when the milk flow to the teat cistern is less than the flow out of the teat canal. This situation leads to teat congestion and can occur at different stages of milking. At the start of milking it can occur when clusters are attached prior to the milk let-down reflex when stimulation was inadequate initiating a bimodal milk flow phase. The latter increases the duration and percentage of low milk flow. This may lead to an inability to harvest 45-50% of milk within the first 2 minutes of milking, increasing the risk of overmilking at the end of milking, due to late removal of clusters (Petzer and Swan 2018). Overmilking may also occur during milking when milk flow is too fast, when the cow excretes adrenalin and the let-down reflex is suppressed or most often at the end of milking when clusters are left on for too long. Bimodality of milk flow was detected if a curve had a flow pattern with 2 increments separated by a clear drop in milk flow for more than 200 g/min within 1 min after the start of milking (Dzidic *et al*., 2004). The strip yield provides an indication of the completeness of milking (Rasmussen *et al*., 1994).

When the vacuum in the teat cistern is higher than the vacuum beneath the teat end for short periods of time, the reverse pressure gradients across the teat canal may damage the teat. According to Rasmussen *et al*. (1994) reverse pressure gradients occur only during milking of empty teats. The mouthpiece chamber vacuum in the liner increases during overmilking, leading to an increase in vacuum fluctuations. Overmilking is extended milking time which leads to teat oedema and hyperkeratosis and increases the risk of new IMI and mastitis (Haman, 1990; Neijenhuis *et al*., 2000; Rasmussen *et al*., 1994; Sandrucci *et al*., 2007).

2.5 Longevity

In dairy cows, longevity is defined as the length of a cow’s productive life (Parker et al., 1960), from first calving to death (De Vries and Marcondes, 2020). This means that the productive lifespan is much shorter than their natural lifetime expectancy. De Vries and Marcondes (2020) stated that the average productive lifespan is between 2.5 and 4 years with an average below 3 years in the United States. There is a daily risk of culling due to clinical mastitis and cows with subclinical mastitis produce less milk and have higher SCC, which leads to an increased risk of culling (De Vries and Marcondes, 2020). Neijenhuis et al. (2001) found that rough teat ends are correlated with an increase in clinical mastitis. This is because rough teat ends are difficult to clean with pre-milking preparation, allowing bacteria to colonize more easily. Reasons for culling usually depends on disposal reasons that show a decrease in health and animal welfare and also on the supply of younger genetically improved heifers (De Vries and Marcondes, 2020).

The milking machine is known to cause short term physiological effects such as tissue swelling, teat congestion, hardness and colour change (Mein et al., 2001). Such physiological changes are associated with the teat canal openness, and the ability for invasive bacteria to penetrate the udder and to cause new IMI new and diminished animal well-being (Wieland et al., 2018). Several associated factors that cause short-term physiological changes have been reported such as vacuum (Rasmussen and Madsen, 2000), pulsation rate (Thomas et al., 1993), pulsation ratio (Thomas et al., 1993), resting or D-phase (Upton et al., 2016a), liner design (Thomas et al., 1991) and milking duration (Hamann and Mein, 1990).

The teat canal is the main barrier that protects the udder from invasive mastitis pathogens. Therefore, the maintenance of good teat skin condition and tissues surrounding the canal is an important part to ensure good milk quality (Zucali et al., 2008). Through the improvement of health, conformation and animal welfare, forced culling will be reduced (De Vries and Marcondes, 2020). This will ultimately lead up to an increase in longevity and allow for improved culling decision making.

2.6 Milking machines

The core purpose of milking is to harvest milk at an optimum speed while maintaining cow comfort and preserving teat defense mechanisms against mastitis pathogen invasion (Penry, 2016). It is therefore of the essence to optimise milking machine settings. Numerous studies have shown that milking speed will increase with increasing milking vacuum (Rasmussen and Madsen, 2000; Spencer *et al*., 2007; Thomas *et al*., 1991). However, this may also increase the risk of teat congestion and micro lesions of the epithelium in the teat cistern, making it susceptible to the colonisation of pathogens within the teat canal (Hamann *et al*., 1994).

2.6.1 Teat liners

Liners are the only part of the milking machine that comes into direct contact with the teat. Teat liners should support the teat integrity and massage the teat by the application of a compressive load (Spencer and Jones, 2000). Liner design is often a series of compromises or trade-offs between competing goals depending on the focus of the liner design. Liners that are designed to reduce liner slip might be uncomfortable or a liner designed to milk faster may leave more milk behind in the udder cistern. There are many different teat liners available on the market to choose from including several types of materials; shapes (round, triangular, oval and square shapes); non-vented or vented (in the short milk tube or mouthpiece chamber), design, liner wall harness, wall thickness and mounting tension. Teat liners are made of natural, synthetic (mostly nitrile) or silicone rubber that affect the liners' lifetime, usually measured in the number of cow milkings or the hours they can be used. Rubber liners are less costly but do not last as long as synthetic mix liners. The lifetime of rubber liners is 600-800, synthetic (blend dependent) 1200-2500 and silicone liners 3000-5000 for cow milkings (Mein *et al*., 2004). Results of many comparative experiments indicate 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, while 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, which is due to the imposed pressure differences across the wall of the liner as the pulsator operates, is important to protect the teats. A cow's teats will stretch up to half its' own length while milking. When a liner fits snuggly at the start of milking, it will prevent too much sideways stretching of the teat. A liner which is too wide will allow the teat to stretch sideways during milking and the teat will shrink in its' length. The net effect of short teats is that the teat liner cannot massage the teat effectively during the d-phase of milking and teat congestion will increase. Teat liners must be long enough to be able to collapse below the teat end and should have a diameter of 1-2 mm less than the average diameter of the teats after milk let-down (in most cases it will be the average teat size on the farm). The teat base diameter is measured midway in the teat length after stimulation (Ohnstad and Reinemann, 2017). According to Ohnstad and Reinemann (2017), liner fit is the most critical component of practical liner application and incorrect liner fit may cause changes to teat diameter.

2.7 Milking machine settings

The pro-active udder health monitoring program is a result of fine tuning of the general udder health monitoring program (Schukken *et al*., 2003). Researchers concluded that optimisation of vacuum setting and liner design could improve milking time and yield.

2.7.1 Pulsation

Pulsation settings on milking machines can affect milking performance (Rosen *et al*., 1983). Teat thickness after milking tends to increase with pulsation ratio, but decreases significantly as the pulsation rate increases between 20 and 80 pulses/min (Hamann *et al*., 1994; Hamann and Mein, 1996).A pulsation rate of 50 to 60 pulses/min is recommended by the ISO 6690:2007 (Milking machine installations – Mechanical tests). Thomas *et al*. (1991) indicated that when the pulsation rate was increased from 20 to 50 pulses/min, the most substantial increase in milking rate was shown, while an increase from 50 to 80 cycles/min did not change milking speed. Østerås *et al*. (1995) found that pulsation rates below 55 cycles/min will affect 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).

Pulsation ratio indicates the ratio between the milking (milk flow) and the resting (massage and no milk flow) phases. Pulsation ratio can be changed to modify peak flow rates (Hamann and Mein, 1996). Specifications for this ratio may vary between milking machine manufacturers but normally range from a 50:50 to 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 purpose of pulsation is to limit development of congestion and oedema in the teat tissues during machine milking (Mein *et al*., 2004). In addition to this primary function, effective pulsation assists to maintain a high milk flow during pulsation, limits discomfort felt by the cow, reduces the incidence of new IMI and stimulates milk ejection. According to Mein *et al*. (2004), depending on the characteristics of the liners used, peak milk flow reaches a maximum level at a pulsator ratio within the range of 60% to 70%. Thomas *et al*. (1991) reported shorter machine-on times and higher milk yields for wide work to rest ratios such as 70:30 compared to ratios of 60:40 and 50:50.

According to Mein *et al*. (2004) pulsation settings that allow the pulsation chamber to return to full atmospheric pressure for at least 150 milliseconds (d phase) during each pulsation cycle, help to overcome teat congestion induced by the system vacuum. When the liner closes during milking, the critical collapsing pressure difference (CCPD) is reached.

According to Spencer (2011) CCPD is 17 to 27 kPa, but liners other than round (oval, square or triangular) will have a lower CCPD. The barrel wall thickness and liner tension affect the CCPD markedly, while rubber compounding has a relatively minor role in influencing CCPD.

Teat-end hyperkeratosis increases with increased pressure applied by teat-cup liners (Hamann *et al*., 1994) and is related to the type of mechanical milking conditions and the length of the teat-cups which are applied to the teat. Compressive load or over-pressure is the pressure applied to the teat by the closed liner. The touch point pressure difference is the average pressure, above atmospheric 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 the touch point pressure difference is the barrel wall thickness of the liner. The touch point pressure difference may range from 30 to 45 kPa (Spencer, 2011).

2.7.2 The milking (system) vacuum

The milking machine settings influence both the milking characteristics and the teat tissue condition (Ambord and Bruckmaier 2010). The vacuum pump generates vacuum for the whole milking system, both milk and vacuum lines and all devices and determines the levels of vacuum in the claw and pulsator chamber. Milking vacuum varies depending on factors such as the lifting height required for milk, milk tube length and diameter, as well as the number and type of devices incorporated into the system (Besier and Bruckmaier, 2016; Spencer, 2011). There is therefore not one milking vacuum level that fits all systems.

There are many indications that a high milking vacuum (50 kPa) may have an increased risk of causing teat tissue damage and hyperkeratosis compared to lower vacuum (42k Pa) (Neijenhuis *et al*., 2001; Reinemann *et al*., 2001). Recovery time of teat tissue post milking was also shown to increase with increased milking vacuum (Hamann *et al*., 1993). Although machine-on time decreased with high milking vacuum, thickness of the teats, both the apex and barrel, increased meaningfully at milking at 40 kPa and 50 kPa compared to vacuums at 25 kPa or 30 kPa (Hamann *et al*., 1993).

Low milking vacuum on the other hand may reduce the effect with 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 that consequently may worsen the condition of the teat end (Reid and Johnson 2003) or may increase the risk of cross infections between quarters during the a-phase of pulsation (Ambord and Bruckmaier, 2010). Contrary to other studies, Besier and Bruckmaier (2016) found that a low milking vacuum of 42 kPa resulted in teat wall becoming thicker resulting in a decrease in teat cistern diameter compared with a system vacuum of 50kPa. Field observations from Norway found improved udder health when cows were milked at a milking vacuum between 48 kPa and 52 kPa (Rasmussen and Madsen, 2000).

2.7.3 Claw (teat end) vacuum

Milking vacuum is one of the two main forces required to keep the liner on the teats during milking (Rasmussen and Madsen, 2000). The milk tube provides vacuum to keep the cluster on the teats and is also responsible to transport milk from the cluster. Vacuum drops are therefore inevitable (Besier and Bruckmaier, 2016). When 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 flow starts and milk is transported from the cluster (Ambord and Bruckmaier, 2010). The vacuum drop is subjected to the technical characteristics of the milking system and to the increases in the milk flow rate (Besier and Bruckmaier, 2016). The highest vacuum drop in high milk-lines occurs during periods of high milk flow rates (Besier and Bruckmaier, 2016).

In high milk-line milking systems milk must be transported vertically in the long milk tube, which causes a loss of vacuum inside the milk tube that lowers the claw vacuum (Østerås and Lund, 1980). In the absence of milk flow, claw vacuum increases to almost similar levels as that of milking vacuum. Increased vacuum in the absence of milk flow will expose teats mainly at the start, (too early attachment or ineffective milk let-down) and end of milking (when milk flow declines or ceases sequentially in individual quarters) to an increased risk of damage (Besier and Bruckmaier, 2016). According to Ambord and Bruckmaier (2010) the vacuum loss in high- and mid-level milk-line systems depends primarily on the amount of milk transported. During high milk flow at the plateau phase, the vacuum loss is particularly high, compared to the start or end of milking when milk flow is low (Ambord and Bruckmaier, 2010; Díaz *et al*., 2004; Østerås and Lund, 1980; Rasmussen and Madsen, 2000). These changes in vacuum cannot be compensated for by an increase of milking vacuum. A drop of the claw vacuum during milking may reduce milking performance through reduced efficiency of milk removal and the vacuum level at the claw (Besier and Brukmaier 2016; Rasmussen and Madsen, 2000).This may compromise the teat condition due to impaired liner closure and reduced pressure of the liner on the teat, hence reduced massage effect of the closed liner on the teat (Hamann *et al*., 1993). Besier and Bruckmaier (2016) suggested 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.

Besier and Bruckmaier (2016) investigated the effects that high milking vacuum have on claw and pulsator chamber vacuum and its effect on milking performance and teat condition using ultrasound. The vacuum in the pulsator chamber did not change during milk flow while the claw vacuum did. These results indicated that low claw vacuum had an influence on milking performance (milk flow) which was independent of the milking vacuum. The teat condition however was mainly dependent on the milking vacuum and the teat tissue load was increased at a higher milking vacuum (50kPa) at the end of milking when milk flow decreased (Besier and Bruckmaier, 2016). It was concluded that ACR should be considered to limit the effects on the teat tissue and postulated a minimal milk loss with shorter machine-on time, by avoiding the lowest milk flow at the end of milking.

Low claw vacuum causes the liner movement within each pulsation cycle, which leads to a prolonged liner-open phase. This can be explained when 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 and Jones, 2000). In addition, a drop of the claw vacuum may increase the probability of liner slips because the adhesion of the liner to the teat is reduced (Baxter *et al*., 1950; Besier *et al*., 2016; Rasmussen and Madsen, 2000; Spencer, 2011; Stewart and Schultz, 1958). The degree of vacuum fluctuations at teat end depends also on the technical characteristics of the milking system and increases with increased milk flow rate. Different claw vacuum levels may influence milking performance and the condition of the teat tissue parameters (Besier and Bruckmaier, 2016; Giesecke *et al*., 1994; Gleeson *et al*., 2002; Mein *et al*., 2001; Mir *et al*., 2015).

2.7.4 Pulsator chamber vacuum

In a two-chamber milking unit, the pulsation chamber is exposed to either pulsator chamber vacuum or atmospheric pressure, by pulsation allowing the liner to alternatively open or close (Neuheuser *et al*., 2017) and to apply pressure on the teat end (Besier *et al*., 2016). The role of the pulsation chamber vacuum is to open the liner allowing milk flow when under vacuum and collapsing the liner under atmospheric pressure (Neuheuser *et al*., 2017). During the normal movement of the liner, milk flow will occur if milk is present in the teat cistern. This is not dependent on the presence of oxytocin. Without the release of oxytocin, there is a probability that all milk would be removed from the cistern before successful milk ejection from the alveoli can occur (Neuheuser *et al*., 2017) leading to bimodal milk flow curves.

In a study by Neuheuser *et al*. (2017) manual pre-stimulation during decrease of pulsator chamber vacuum was compared. A milking vacuum of 42 kPa, a pulsation ratio of 60:40 was used and the pulsator chamber vacuum was reduced to 20 kPa to prevent opening of the liner (preventing milk flow from the teat cistern). Neuheuser *et al*. (2017) stated that the released oxytocin led to quick and complete milk removal compared with after manual pre-stimulation. Thus, reduced pulsator chamber vacuum is an appropriate pre-stimulation in modern dairy practice. Therefore, after a short teat cleaning, direct attachment can be made and can prevent bimodal milk flow curves during this period (Neuheuser *et al*., 2017).

2.7.5. Mouthpiece chamber vacuum

The purpose of the mouthpiece lip is to seal at teat base in order to maintain vacuum during milking. Stiff mouthpiece lips occlude blood supply and cause ringing while soft flexible lips allow passage of tissue fluids in teats (Rasmussen,2017).

The mouthpiece chamber vacuum of liners is quite variable but important. Liners with shallow mouth piece chambers have lower vacuum than those with deep chambers. Deep mouth piece chambersmay prevent teats from entering the zone of adequate liner compression mainly when short teats are milked. A practical way to aid in the selection of the correct mouth piece chamber length for a herd would be to use the following calculation. For a liner with a mouth piece chamber depth of 30 mm, teats should at least be 39mm long (30mm + 25mm / 1.4) (Ohnstad and Reinemann, 2017). The mouth-piece chamber vacuum decreased in old liners. According to Ohnstad and Reinemann (2017) and Rasmussen (2017) the ideal mouthpiece chamber vacuum should be less than 10 kPa and teat congestion can develop when the vacuum exceeds 20 kPa.

Different adjustments of single components can shift the air and milk streams in the milking machine and lead to changes in vacuum behaviour of the claw and mouthpiece chamber (Bluemel *et al*., 2016). At the start of milking, vacuum is relatively low and stable in the mouthpiece. Towards the end of milking, claw vacuum generally increases and vacuum fluctuation dramatically increases in relation to pulsator frequency. High mouthpiece vacuum is associated with an increased frequency of tissue stress which results in a higher risk of infection and mastitis. Borkhus and Ronningen (2003) studied mouthpiece chamber vacuum during the different milk phases. A more stable mouthpiece chamber vacuum was detected during peak milk flow but there was an increased mouthpiece chamber vacuum and increased fluctuations due to pulsation during low flow. When teats are exposed to teat-cup liner conditions, some congestion and oedema of the teat end occurs at the end of peak milk flow, even when using universally accepted milking machine settings (Neijenhuis *et al*., 2001). With different settings of the milking machine, such as vacuum level, volume of cluster removal and pulsation rate the teat thickness varies (Hamann, 1990; Hamann *et al*., 1993; Rasmussen, 1993; Hamann and Mein, 1996; Neijenhuis *et al*., 2001).

2.8 Combined effects

2.8.1 Liner compression and overpressure

It is important to understand the role of liner compression (LC) in order to obtain a balance between gentle milking and speed. Liner compression increases during milking as claw vacuum decreases. When the milking vacuum is lowered the compressive load applied by the liner is also 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, blood and tissue fluids accumulation in the teat tissue may initiate teat congestion and oedema (Leonardi *et al*., 2015; Upton *et al*., 2016b). According to Upton *et al*. (2016b) liner compression assists venous flow with removal of fluids that are accumulated in the tissue of the teat-end. Liner compression is described by Mein *et al*. (2003) 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 the LC. 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 slower post milking and can result in a higher rate of IMI. Teat end congestion can be relieved by an adequate magnitude and duration of LC during the d-phase of the pulsation cycle (Upton *et al*., 2016a), but only when the d-phase duration is sufficient (Hamann and Mein, 1988). The International Organization for Standardization (ISO) specifies a minimum d-phase duration of 150 ms per pulsation cycle (ISO 6690:2007). Hamann and Mein (1996) found that a d-phase exceeding 150ms had little additional benefit to decrease congestion or increase in milk flow rate.

Liner compression is also a function of the physical dimensions of the liner (Leonardi *et al*., 2015), primarily the wall thickness (Bade *et al*., 2009). Less LC is experienced with soft silicon liners than with rubber liners and it is higher in round compared to triangular liners. The length, diameter and shape of teats influence LC. It is higher in teats with a big apex and in congested teats, but lower in long teats (Mein and Reinemann, 2009).The degree of compression applied to the teat by the liner has a marked influence on the teat condition (Mein and Reinemann, 2009) as it effects the comfort of the cow, teat condition and peak milk flow rate.

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

2.8.2 Peak flow rate

Neuheuser *et al*. (2017) defined peak flow rate in a milking as the maximal milk flow rate which continues for at least 22 seconds. Early work by Dodd and 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 degree of liner compression (Bade *et al*., 2009; Reinemann *et al*., 2008). The main and interactive effects on peak milk flow rate were studied by Bade *et al*. (2009) by independently controlling variables over a wide range of settings. Milking vacuums of 42 k Pa to 53 kPa, b-phase durations from 220 ms to 800 ms and LC of 8 kPa to 14 kPa were examined. The study found that increasing the vacuum and the b-phase duration always increased peak milk flow rate and increasing LC also increased peak flow rates with a greater effect at higher vacuum.

In a study by Reinemann *et al*. (2008) the claw vacuum was altered while keeping overpressure at 8 kPa and b-phase length at 800ms.Contrary to findings of Bade *et al*. (2009) the peak milk flow was reduced when claw vacuum increased from 40 kPa to 46 kPa. When the overpressure was increased to 11 kPa at a claw vacuum of 46 kPa and a 800ms b-phase duration, the peak milk flow increased and it increased further when overpressure was increased to 14kPa. However, a critical level of overpressure ranging between 8 kPa to 12 kPa is required to control teat congestion during milking (Reinemann *et al*., 2008). Poor teat end condition and discomfort is seen when overpressure exceeds 8 kPa to 12 kPa (Mein *et al*., 1987; Reinemann *et al*., 2001; Reinemann *et al*., 2008; Zucali *et al*., 2008).

2.8.3 A liner performance map

Table 2.1. An example of a liner performance map showing maximum average flow rate (%)

	Milking speed and liner compression of a specific liner Triangular with 5 kPa overpressure)						
Teat end vacuum	**B-phase (ms)**						
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 1st column indicate congestion of teats <3cm long	**Table colours indicate congestion for teats >3cm long**			**Low**	**Medium**	**High**	**Extreme**

(Ohnstad and Reinemann, 2017)

The main machine settings affecting the milking speed are claw vacuum, the duration of the b-phase and the liner overpressure. Each liner design should have a unique liner performance map from the manufacturer. The liner performance map in Table 2.1 is for a particular triangular liner with an overpressure of 5 kPa. There are 3 variables indicated, namely the teat length (below 3cm or ≥ 3cm), claw vacuum (34 kPa to 47 kPa) and the duration of the b-phase (300 ms to 600ms). For example: at a teat end vacuum of 36 kPa, a maximum milking speed of 82% can be achieved in teats ≥ 3 cm when the b-phase setting is 550 ms to 600ms. At this setting however, there is a medium risk of teat congestion. At the same vacuum level with a b-phase setting of 500ms, a milking speed of 81% will be achieved with a low risk of teat congestion (Table 2.1).

2.9 Automatic cluster remover

When set correctly, an ACR will prevent potential overmilking damage (Rasmussen *et al*., 1994; Tangorra *et al*., 2010) leading to udder health improvements (Ginsberg *et al*., 2018). In addition, it relieves the operators to remove the cluster manually to increase milking efficiency. Increasing the switch-point at which clusters are removed may shorten milking time and increase milking efficiency (Krawczel *et al*., 2017). This is because of a shorter duration of milking time during the time that the milk flow is low, nearing the end of the milking curve. Krawczel *et al*. (2017) stated that standard milk flow curves may be used to determine the setting for termination of individual milkings. Tancin *et al*. (2006) divided the milk flow curves into four phases: increase, plateau, decline and overmilking. The initial flow of milk or increase phase is usually milk from the cisterns and large lobes being milked (Ginsberg *et al*., 2018). If there is no pre-stimulation the milk flow stops after small amounts of cisternal milk (bimodal milk flow). Ginsberg *et al*. (2018) explained that this is important in late lactation cows, as initial delay times may cause the ACR to remove the cluster for such cows. Therefore, in herds with poor stimulation, kick-offs and 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). In order to maximise parlour efficiency and minimise overmilking, the optimal termination point is in the decline phase of the milk flow curve, before the overmilking phase begins (Krawczel *et al*., 2017; Tančin *et al*., 2006). Excessively high vacuum (>50kPa) has been shown to increase hyperkeratosis, or formation of callus-like tissue at the teat end, as does overmilking (Spencer, 2011). Ginsberg *et al*. (2018) summarised the claimed advantages of ACR as a decrease in over-milking, improved teat condition, labour saving and a more consistent milking routine. Disadvantages of an ACR unit are the cost of installation, maintenance and reliability (Ginsberg *et al*., 2018).

2.9.1 Take-off settings

Take-off setting differ between machine manufacturers.

- Take-off limit (switch point) is the setting that will activate the ACR when the milk flow decreases beyond this level (Jago *et al*., 2010).
- Post milking is described as the time from when the take-off limit is reached, to the time that the vacuum will be cut.
- Take-off delay is the time from when the vacuum was cut, till when the ACR pulls to remove the cluster.
- Maximum pre-milk time and maximum second pre-milking time, determine the minimum time that the cluster will be attached to the teats for the first and consequent attachments within the same milking.
- Low-flow limit is the flow rate that the machine uses to change from the pre-milking phase to the main-milking phase.

There are no ISO standards for ACR that would give the correct setting formulas to apply 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) in situations where the work routine times of dairy operators can be accelerated (Edwards *et al*., 2013). According to Ginsberg *et al*. (2018) additional to the switch-point, the flow rate at cluster removal depends on final delay time and milk flow rate near the end of milking. This means that in cows with a rapid decrease in milk flow, overmilking can occur, where cows with slow flow rates will be less influenced. The decline in flow rate will depend on the milking vacuum (Ginsberg *et al*., 2018).

Table 2.2. Studies of changes of ACR switch-point settings

References	Number of cows	Duration of study	Milkings per day	Threshold (g/min)	Delay time (s)	Machine-on time	Milk yield (kg)	Teat condition	Udder health
Sagi, 1978	16	3	2	200 400		-0.45**	NS		
Rasmussen, 1993	135	36	2	200 400	18 12	-0.52*	NS	Improve	NS
Reid and Stewart, 1997		-	3	300 – 450 200 – 900	12 – 7 15 - 3	-1.4 -1.2	Increase Increase		
Stewart *et al*., 2002	3588	2-4	2	500 – 640 730 – 820	1 - 1 1 - 1	-0.25**	0.18+		
Bandosova *et al.,* 2003	39	3	2	300 405 540		-0.4 -0.6	NS		
Magliaro and Kensinger, 2005	60	12	2	480 600 800		-0.4** -0.7**	-0.4**		
Jago *et al*., 2010	378	35	2	200 400		-0.7***	NS	NS	NS
Edwards *et al*., 2013a	96	8	2	200 400 600 800		-0.68*** - 1.05*** - 1.20***	NS		NS
Edwards *et al*., 2013b	96	11	2	200 400 600 800		-0.67*** - 0.80*** - 1.30***	NS		NS

NS: Not Significant; SCC: Somatic Cell Counts; + p<0.1; * p<0.05; ** p<0.01; *** p<0.00

(Ginsberg *et al.,* 2018)

2.9.2 Automated cluster removal setting and parlour efficiency

Early studies by Sagi (1978) and Rasmussen (1993) concluded that the cluster can be detached at a flow rate of 0.4kg/min. In 2010 a study in Israel showed that 19 of the farms surveyed using Afimilk equipment had switch point settings above the factory default of 0.480 kg/min and only 6 farms did not change the default settings (Ginsberg, 2011). A milk flow of below 0.2 kg/min is considered as low for dairy cows (Ginsberg, 2011) and the cluster should be removed before such a low flow rate to prevent teat damage. The use of ACR that has been adjusted for optimal levels of operating milk flow threshold and delay time, reduces the milking duration while maintaining milk quantity and teat canal integrity (Rasmussen, 1993). Some manufacturers enable the farmer to change the take-off settings, allowing the farmer to adapt his parlour to ensure optimum milk production. Cluster removers have promoted profitability in dairy operations from their introduction by increasing automation of milking, decreasing labour and improving efficiency of the milking process (Ginsberg *et al.,* 2018).

Recent studies show that clusters can be detached early, without loss of milk yield. The cluster-on time of individual cows is an important factor determining herd milking times and thus labour requirements (Edwards *et al*., 2013a). With increasing herd size, a reduction in the availability of skilled labour and a need to minimise operating costs, on-farm milking practices that improve labour productivity (cows per labour unit) need to be examined (Jago *et al*., 2010). 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). A study by Clarke *et al*. (2004) combined the traditional ACR milk flow switch rate with an ACR delay time (max cluster attachment duration) to limit the effect of the slowest 20 % to 30% of cows in a herd on total milking time. It 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 SCC or incidence of clinical mastitis (Clarke *et al*., 2004; Clarke *et al*., 2006a; Clarke *et al*., 2006b).

A study completed by Jago *et al*. (2010) evaluated the effect of 4 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 four treatments were 0.2 kg/min; 0.4 kg/min; 0.2 kg/min at a maximum cluster attachment time from day 5 of lactation (MaxTEarly); 0.2 kg/min until an average of 63 ± 21 days in milk, then cluster removed at a milk flow rate of 0.2 kg/min or a maximum cluster attachment time (MaxTPeak). Jago *et al*. (2010) found that milking duration was shorter for 0.4 kg/min, MaxTEarly, and MaxTPeak compared with 0.2 kg/min. No differences were observed in neither teat condition nor the proportion of cows with at least 1 case of clinical mastitis during the trial period. Somatic cell count was low across 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 milking duration was decreased without affecting milk production, clinical mastitis or teat condition. This study concluded that combining a switch point setting with a maximum cluster attachment time during early or peak lactation, reduced milking duration without negative effects.

Automatic cluster remover settings have the potential to improve milking parlour efficiency and improve animal well-being. The recommendation of Ginsberg *et al*. (2018) was that it should be removed at a flow of more than 400 g/min. Besier and Bruckmaier (2016) suggested a milk flow threshold of up to 1kg/min. Erskine *et al*. (2019) applied a threshold of 1.1 kg/min and Wieland *et al*. (2017) found that the increase of the cluster remover take-off milk flow threshold even further to 1.2kg/min caused a significant decrease in milking duration. Wieland *et al*. (2017) concluded that this resulted in a significant decrease in milking duration, improving teat tissue condition without negatively affecting milk production, milk component yields, or udder health because of a reduction in overmilking time.

Understanding how milking machine settings influence the udder milk flow rate is important for the development of best practice parameters for machine settings and for appropriate sizing of milking facilities (Upton *et al*., 2016b; Reinemann *et al*., 2016a). New studies are placing more emphasis on quarter milk flow patterns because they offer biological information that is needed for improving machine milking and the welfare of cows (Tancin *et al*., 2006). With conventional milking machines the entire cluster is removed at the same time and this may result in some quarters being overmilked in comparison to others (Ginsberg *et al*., 2018).

2.10 Digital vacuum recorders and milk flow dynamics

Analysis of milk flow dynamics can improve udder health and milking efficiency by highlighting opportunities to improve milking protocols and equipment function that align with the physiology of the cow (Sandrucci *et al*., 2007). Some instruments can be used to assess milking dynamics by measuring the milk flow, such as the VaDia that records the vacuum in the milking unit and assists with the estimation of key changes in the milk flow. VaDia digital vacuum recorders (Biocontrol, Rakkestad, Norway) measure simultaneous vacuum events during milking in 4 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, in order to collect data from different cows on different strings. The mouthpiece chamber vacuum is strongly and negatively correlated with milk flow and positively associated with teat congestion (Borkhus and Rønningen, 2003; Penry *et al*., 2018b). The pattern of milk flow in individual quarters has 4 phases of intensity: incline, plateau, decline and overmilking (Tančin *et al*., 2007).

Moore-Foster *et al*. (2019a, 2019b, 2019c) investigated using a Vadia, whether milking vacuum measured in the short milk tube and mouth piece chamber with digital recorders, could serve to identify key time points of phase changes in milk flow. In addition, the effect of the lag period between cluster attachment and milk let down in relation was studied. It was concluded that insufficient stimulation prior to milking results 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 (Bruckmaier, 2005; Erskine *et al*., 2019; Moore-Foster *et al*., 2019a).

Malmo and Mein (2015) found a strong relationship between higher milk flow and lower milking unit vacuum being recorded simultaneously. Milk flow was demonstrated using a

LactoCorder (WMB AG, Switzerland) and milking unit vacuum using the VaDia (Biocontrol, Rakkestad, Norway). Borkhus Rønningen (2003), supported the fact that vacuum can be used to establish key points in the milking curve and that marked changes in mouth piece chamber vacuum can be used to 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 and Mein (2015), who found that estimated let-down time, when measured either by actual milk flow or milking unit vacuum, were highly correlated (R2 = 0.81). Erskine *et al*. (2019), concluded that milk flow analysis by the use of the small milk tube vacuum and the mouth piece chamber vacuum served as a useful indicator for delayed milk ejection, bimodality. This also assisted with the estimation of the let-down time in a herd milking three times per day, since milk yield is negatively associated with increased let-down time.

2.11 Concluding remarks

The research completed in this study includes an extensive literature study regarding the effects of milking machines on udder health. The general purpose of milking machines is to harvest milk at an optimum speed while maintaining cow comfort and preserving teat defense mechanisms against mastitis pathogen invasion making machine settings a priority in dairy herds.

Liners are the only part of the milking machine that meets the teat. Teat liners should support the integrity of the teat and massage the teat by application of a compressive load and should be the correct size. The size and length of teats may vary between cows within a herd and with parity and teat size should be determined to select a suitable size for the herd. Each liner design should have a unique liner performance map from the manufacturer which can be used to determine the milking speed and liner compression for a specific liner.

In South African many swing-over parlours were installed with a flowmeter far above the cow’s udder which led to an increase in the delay time of the ACR activation. This increases the risk of overmilking and increases the risk of IMI as a consequence of this. There are ISO guidelines for milking machine installations, construction and performance, but there are currently no ISO standards to set ACR switch-point settings with most farmers using default milking machine settings. When the ACR is set correctly it will prevent potential overmilking damage leading to improved udder health. An increase of the ACR switch-point setting may shorten milking time, decrease overmilking and increase milking efficiency. The improvement of ACR settings has the potential to improve milking parlour efficiency and improve animal well-being. Analysis of milk flow dynamics using the VaDia can improve udder health and milking efficiency by highlighting opportunities to improve milking protocols and equipment function that align with the physiology of the cow.

Analysis of milk flow dynamics can improve udder health and milking efficiency by highlighting opportunities to improve milking protocols and equipment function that align with the physiology of the cow. Instruments including the VaDia can be used to assess milking dynamics by measuring the milk flow and vacuum in the milking unit to estimate key changes in the milk flow curve.

2.12 References

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Chapter 3

The effect of different automatic cluster removal switch-point settings on milking and overmilking duration and on total, peak and overmilking claw vacuum.

3.1 Abstract

The ideal milking machine harvests milk from dairy cows in a fast, effective manner without causing teat or udder damage, cow discomfort or loss in milk quality. The aim of the study was to investigate the effect of three automatic cluster removal (ACR) switch-point settings on machine-on time, overmilking duration and total mean-, peak flow- and overmilking vacuums. In a randomised trial (using 65 cows) conducted on a research dairy herd, cows were exposed to three ACR switch-point settings (0.504 kg/min, 0.630 kg/min and 0.840 kg/min) for 15 milkings per setting over an 8-week period. The milking parlour was a 10-point, low milk-line, herringbone Waikato machine with the Afimilk system. Pre-milking preparations were observed, while a VaDia BioControl (Vadia) apparatus was used to determine machine-on time and vacuums at the claw, mouthpiece- and pulsator chambers during the whole milking process. Results indicated that machine-on time varied from 290, 289, 303 seconds for 0.840, 0.630 and 0.504 kg/min settings respectively. Overmilking duration differed significantly ($p<0.0001$) from 77 to 108 seconds between the highest and lowest volume settings. Vacuum levels differed ($p<0.0001$) at each switch-point setting. This study indicated that while machine-on time was decreased by 4.4 %, the period of overmilking was 29.3 % shorter and the vacuum during overmilking was 3.7 kPa lower when an ACR switch-point setting of 0.840 kg/min was used compared to 0.504 kg/min. Similarly, overmilking duration was 26.4 % less and overmilking vacuum was 4.3 kPa lower, when an ACR switch-point setting of 0.840 kg/min was used compared to 0.630 kg/min. The knowledge gained from the use of different switch-point settings can be applied on individual dairy farms using different parlours and milking machines, to optimise settings in order to obtain a balance between milking efficiency, udder health and cow comfort. The use of the correct ACR switch-point setting (0.840 kg/min) lowered the risk of teat end damage due to shortening machine on time and decreasing the overmilking duration and the vacuum level.

Keywords: milking machine**,** switch-point settings, overmilking duration, claw vacuum

3.2 Introduction

Advances in animal genetics, milking machine design, nutrition and management have led to a 6-fold increase in production per cow over the past 100 years (Jacobs and Siegford, 2012). This is a considerable increase in milk production with a sharp decrease in the total number of cows in the United States (Jacobs and Siegford, 2012). Milking machines remain the main challenge to the primary immune system of the bovine udder. Mein (2012) reported that the inside of the cluster, at the teat, is where the business-end of the complex milking machine interacts with the teat end. In South Africa there was an increase in average herd size (167 to 354 cows) and a 26% increase in milk production (2.6 to 3.3 tons), from 2009 to 2017 (Lactodata, 2013; Lactodata, 2018).

An ideal milking machine harvests milk from dairy cows in a fast, effective manner without causing teat or udder damage, cow discomfort or loss in milk quality. Although development of milking machines has advanced over the years (Jacobs and Siegford, 2012) and there has been a shift from fast milking to the preservation of the teat canal and longevity of the cow (Stefani *et al*., 2018), machine milking still poses challenges to udder health. Instrumentation such as the VaDia is now available for more accurate determination of actual cluster take-off time. Field experience has shown that economic pressure led to swing-over dairy parlours with high milk-lines (HL) being favoured in South Africa (I.M. Petzer, personal communication, May, 2019). The height of the milk line in the milking parlour, is related to the cost of installation while having possible effects on udder health, milking efficiency and milk quality (Díaz *et al*., 2004). The installation of HL systems has a lower cost with greater milking efficiency compared to that of low line systems (Ambord and Bruckmaier, 2010). However, low line systems allow milking to occur at a lower vacuum level (Fernández *et al*., 1997) and can maintain a more stable vacuum at udder level. Fluctuations in vacuum may expose the teat and have a negative influence on teat condition (Østerås and Lund, 1980) as the prevalence of sub-clinical mastitis increases (Østerås and Lund, 1988).

The teat-end is considered to be the first line of defence against mastitis as it allows (or prevents) entry for invading pathogens and is therefore the primary defence mechanism of the udder (Khan and Khan, 2006). Milking machines induce short-term changes that are linked to the weakening of the teats' defence mechanism which may cause the teats to be more susceptible to intramammary infections (IMI) (Niejenhuis *et al*., 2001). Milking performance can be affected by changes in pulsation ratio, pulsation rate and vacuum (Rosen *et al*., 1983). During machine milking, milk is removed under vacuum. Different levels of claw vacuum during machine milking, may affect milking performance and teat condition (Besier and Bruckmaier, 2016).

For decades, researchers have evaluated associations between milk harvesting indicators and occurrence of clinical and subclinical mastitis (Dodd *et al*., 1969; Penry *et al*., 2017). A pro-active approach towards the prevention of mastitis by the dairy industry is the most effective approach, due to low overall success rate of the treatment of mastitis (Petzer *et al*., 2016). A pro-active approach includes optimal milking machine function, timely unit attachment and detachment, proper milk let-down, quiet cow handling, effective identification of mastitis, effective cleaning, timely unit adjustment and alignment and optimal nutrition (Rasmussen, 1994; Schukken *et al*., 2003). The pro-active udder health approach followed in South Africa includes routine milk samples of all lactating cows for monitoring of microbiology and cytology (Petzer *et al*., 2016).

The cost of labour increases with increasing herd size, thus producers are installing automatic cluster removers (ACR) to increase automation and profitability (Wieland *et al*., 2020). The operating principle for ACR is to detach the cluster once milk flow has decreased below a pre-set level or switch-point (kg/min). There are additional adjustments including the ACR delay time which determines the duration that the cluster remains attached after the switch-point is reached (Jago *et al*., 2010). The ACR aims to prevent overmilking and aids in the maintenance of the teat condition (Nickerson and Oliver, 2014). Overmilking starts when the milk flow to the teat cistern is less than that of the flow to the teat canal (Rasmussen, 2000). The main cause of overmilking is an extended milking time. This can occur during low milk flow because of incorrect settings of ACR, manual removal of clusters by milking personnel, or re-attachment of clusters after milking (Rasmussen, 2000). The use of ACR has led to a significant reduction in overmilking (Tangorra *et al*., 2010), due to a shorter duration of the low milk flow time when taken off near the end of the milking curve.

The objective of this study was to investigate the effects of three ACR switch-point settings on milking and overmilking durations, total vacuum and the relationship between overmilking vacuum and peak milk flow vacuum.

3.3 Materials and methods

3.3.1 Dairy herd and study population

The study was conducted at the Research Farm of the University of Pretoria, South Africa (Hillcrest Campus). Animals were fed total mixed rations (TMR) and milking was done three times a day. One milking per day was selected to conduct the trial. The milking parlour used was a 10-point, low milk-line, herringbone, Waikato milking machine (New Zealand, LP) with the Afimilk (Afikim, Israel) program. The herd consisted of 80 lactating cows at the time of the study which were milked three times per day, with an average daily milk yield of 35 kg per cow per day. The herd is on total mix ration and calves all year round.

Selection of cows to participate in the study was based on the following criteria. Udders of all lactating cows in the herd were palpated to identify meaningful fibrosis and nodules in the udder parenchyma. Teat sizes were measured using a DeLaval measuring apparatus just prior to milking, after the letdown reflex had occurred. The criteria for exclusion of cows from the study were: cows within 10 days post calving and those within 45 days of drying-off, cows with asymmetric udders or where fibrosis or nodules could be palpated in the udder parenchyma and cows with teats equal to or shorter than 3 cm (due to the increased risk of bad liner fit and liner slip). The application of these criteria led to 65 cows out of the total 80 cows in lactation in the experimental herd being used for the study. Five cows were too close to drying-off, 1 was within 10 days post calving, 6 had too short teats and 3 cows had asymmetric udders with either fibrosis or atrophy.

For each switch point setting the same 65 study cows were evaluated for 15 milkings over a three-week period. The total VaDia readings for the three switch-point settings are 975. The three switch-point settings were tested in series with an adaption period between the studies.

3.3.2 Experimental design

3.3.2.1 Milking machine settings

The milking machine was tested (static and dynamic tests) just prior to the start of the study to ensure effective functioning. All milking machine settings, except the switch-point volumes, were consistent throughout the study. The pulsation ratio was 65:35 with 60 cycles/min, the milking (system) vacuum was 43.5 kPa with the second minute teat end vacuum of 37.6 kPa for the average producers with an average fluctuation of 2.1 kPa.

Parameters of automatic cluster removal (ACR) settings

The Afimilk milk meter detects the milk flow rate and uses this in order to determine the end of milking. The following settings can be adjusted to achieve the required results: F1, F2, F3, F4 and Ct.

- Pre-milk time (F1) is the minimum time that the cluster is attached to the teat, with a default setting of 120 sec to 180 sec (the value of F1 needs to be multiplied by 10).
- ACR delay (F2) determines the flow rate at which the milking will end. Between 200 kg to 220 kg of milk are released every time the valve of the milk flow meter opens. In this study 210 kg was used to complete the calculations for milk flow rate (MFR) which was calculated as follows:

$$\boldsymbol{MFR = \frac{60\ seconds}{F2\ Value} \times 0.210\ kg\ per\ minute}$$

  Default settings varied from 18 sec (0.700 kg) to 22 sec (0.573 kg).
- Vacuum to removal delay setting (F3) controls the time delay between the vacuum shut-off to the claw piece and the beginning of cluster removal time (default setting of 1 sec to 5 sec).
- The automated quick removal setting (F4) activates removal of the cluster before the delay time designated in F2 is reached under the following three conditions: when the ACR pre-milk time is exceeded, when the harvested milk yield exceeds the expected milk yield and when the meter is filled up by less than half after 50% of the ACR delay time.
- Maximum cluster time on (Ct) measured in units of half minutes (30 sec).

For this study the F2 settings of 15 sec, 20 sec and 25 sec were chosen which corresponded to ACR switch-points of 0.840 kg/min, 0.630 kg/min and 0.504 kg/min respectively, which were compared during this study. The switch-point setting of 0.504 kg/ml (25 sec) was chosen as starting point for the study for being the current setting used in the experimental herd. According to new research data earlier take-off seemed variable. This selection of the settings was based on previous research, see summary of changes of ACR setting from literature (Table 2.2) (Bandosova *et al*., 2003; Edwards *et al*., 2013a; Edwards *et al*., 2013b; Ginsberg *et. al.,* 2018; Jago et al., 2010a; Magliaro and Kensinger, 2005; Rasmussen, 1993; Reid and Stewart, 1997; Sagi, 1978; Stewart *et al*., 2002). The F1 was 120 sec, F3 setting was 3.5 sec, sweep delay and duration was .0 sec and 2.0 sec respectively.

3.3.2.2 Milking parlour activities

Interpretive guidelines described by Moore-Foster (2019a) on parlour behaviour and milking dynamics were noted. Milking events of cows that were observed and recorded included time from first stimulation to cluster attachment (latency period), second minute milk flow and cow behaviour during the complete milking. Events like clinical mastitis, vacuum loss, liner slip, cow comfort (shifting of weight), cluster fall-off and cluster kick-off were recorded and were excluded from the final data set.

Data of all VaDia graphs that were incomplete (pipe damage, cows standing on pipe and anything causing graphs to be unclear) were not included in the calculations.

3.3.3 VaDia Biocontrol measurements

Three VaDia units were calibrated just prior to the study. In a pre-study trial, the results of the 3 VaDia units were compared for accuracy and precision of results.

The VaDia is an apparatus capable of measuring vacuum in 4 channels simultaneously and these results are tabulated and illustrated graphically by the VaDia Suite software (Biocontrol, Rakkestad, Norway). Measurements were taken with the VaDia in the mouthpiece chamber (MPC) of the liners from the front and rear teats, the vacuum in the short milk tube (SMT) as a proxy for claw vacuum and the vacuum in the short pulsator tube (SPT) that indicates the vacuum in the pulsator chamber. This was done for the duration of the milking. The results of the VaDia were monitored in real time via Bluetooth technology during the milking and were downloaded and reviewed by two investigators using the VaDia Suite software.

Four phases of flow intensity were identified: incline, plateau, decline and overmilking phases, as described by Tančin *et al*. (2006). Guidelines from Tančin *et al*. (2006) and practical markers provided by Greenham (personal communication, March 2019) were used to determine the following criteria: the start of milking (when vacuum first increased in any of the MPC or SMT); start of the incline phase of milk flow (almost simultaneous with start of milking); start of overmilking and the end of milking (point where all MPC and SMT traces return to the non-milking vacuum level or 0 kPa). The start of overmilking was logged when the mean MPC vacuum increased by >50% and the MPC vacuum range increased by >50% and this pattern was maintained for the rest of milking, then this was the overmilking period and the marker was positioned at the start of this period.

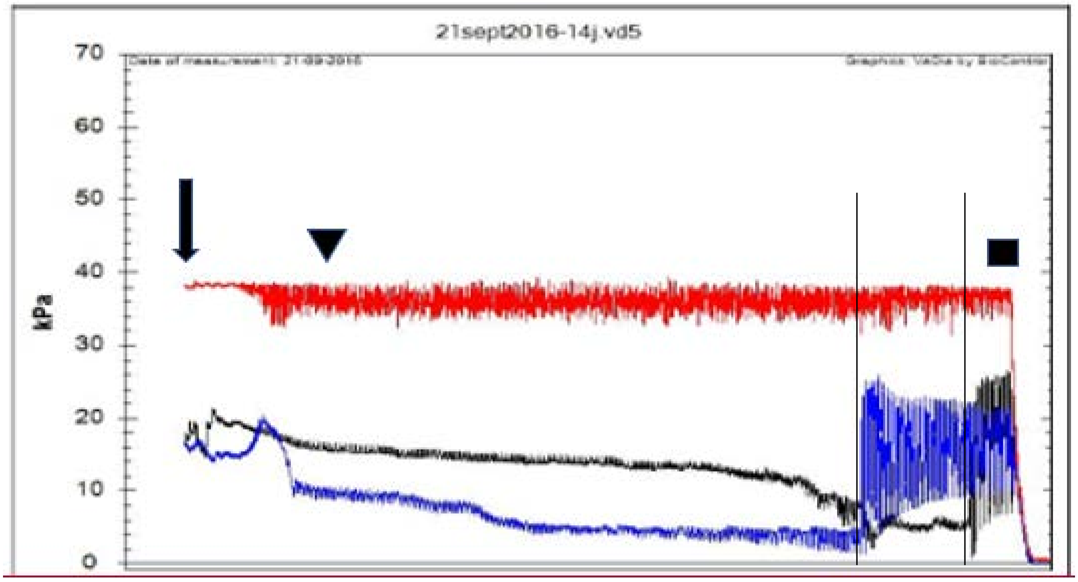


Figure 3.1: Examples of a VaDia Biocontrol, digital recording that indicates the starting point of overmilking for hind and front quarters

For each milking of each cow vacuum (kPa) is recorded on the vertical axis and time intervals (sec) on the horizontal axis. Symbols mark the start of milking (⬇); start of peak milk flow (▼); start of overmilking 1 and 2 with vertical lines; and end of milking (■). Channel 1 (red) was connected to the rear mouthpiece chamber, channel 2 (black) to the front mouthpiece chamber and channel 3 (green) to the short milk tube.

3.3.4 Statistical analysis

The three different ACR switch-point settings were compared using the Kruskal-Wallis test followed by pairwise comparisons with the Wilcoxon rank summary test in order to compare the differences of machine-on time, overmilking duration, milk yield, mean total claw vacuum, mean claw peak flow vacuum and mean claw overmilking vacuum. Rank summary tests were applied as none of the distributions of the different factors were normally distributed, even after transformation of the data. The Bonferroni p-value adjustment method of pairwise comparison (Benjamini & Hochberg 1995) was applied in order to take the family-wise error rate into account. The Shapiro-Wilkinson normality test was used to evaluate the distribution of normality for each of the factors. Boxplots (five-number summary with the minimum, first quartile, median, third quartile, and maximum) were drawn for each of the three switch-point settings of machine-on time, using R software© version 3.3.3.

3.4 Results

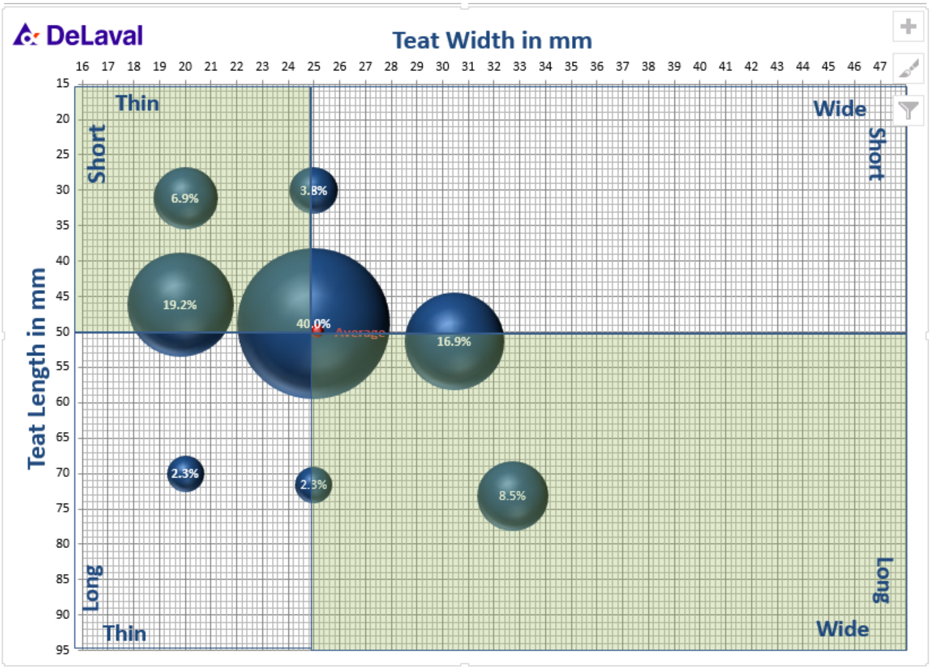
The average length and width of the front and rear teats of cows that participated in the trial after letdown were 5.9 cm and 2.7 cm and 4.1 and 2.4 cm respectively.

Table 3.1: Average teat sizes of the cows in the study herd, using the DeLaval measuring apparatus

Measurement of teat sizes (cm)				
	Front teats		**Rear teats**	
	Length	**Width**	**Length**	**Width**
Average	5,9	2,7	4,1	2,4
Standard Deviation	1,1	0,5	0,8	0,3
Minimum	4	2	3	1,5
Maximum	9	4	6	3
Median	6	2,5	4	2,5

Table 3.2: Teat size distribution of the cows in the study herd

	Teat size distribution								
	Short and Thin	**Short & Ave.**	**Short & Wide**	**Ave. & Thin**	**Average**	**Ave & Wide**	**Long & Thin**	**Long & Ave.**	**Long & Wide**
	L < 35 x W <24	**L < 35 x W 24-27**	**L<35 x W>27**	**L 35-60 x W<24**	**L35-60 x W24-27**	**L35-60 x W>27**	**L>60 x W<24**	**L>60 x W24-27**	**L>60 x W>27**
	7%	**4%**	**0%**	**19%**	**40%**	**17%**	**2%**	**2%**	**8%**
Width	20.00	25.00	0.00	19.80	25.00	30.45	20.00	25.00	32.73
Lenth	31.11	30.00	0.00	46.20	48.85	51.36	70.00	71.67	73.18



Graph designed by Nils Alveby (DeLaval)

Figure 3.3: A graph indicating the teat size distribution of cows in the study herd

Similar VaDia readings per switch-point setting were excluded from the final data set.

Table 3.3: Parlour observation and data exclusions for the three switch-point settings

	Switch-point settings			**Total**	**Percentage of data exclusions**
	0.504 kg/min	**0.630 kg/min**	**0.840 kg/min**		
Number of milkings evaluated (Tests performed)	**15 (315)**	**15 (315)**	15 (315)	45 (945)	
Reasons for data exclusions					
Wrong cows milked	8	9	8	25 (2.7%)	18.8%
Incomplete data	8	5	8	21 (2.2%)	15.8%
Liner slip	14	16	15	45 (4.8%)	33.8%
Kicked at end of milking	3	8	3	14 (1.5%)	10.5%
Vacuum failure (fall-off)	4	5	4	13 (1.4%)	9.8%
Leakage on VaDia pipes	4	3	6	13 (1.4%)	9.8%
Clinical mastitis	1	0	1	2 (0.3%)	1.5%
Total data excluded	**42**	**46**	**45**	**133 (14.1%)**	
Additional parlour observations					
Cows uncomfortable at end of milking (shift weight)	7 (2.2%)	18 (5.7%)	0	25 (7.9%)	N/A
Ring or slight swelling evitable on teat base after cluster removal	6 (1.9%)	7 (2.2%)	1 (0.3%)	14 (4.44%)	N/A

Second minute milk flow values were calculated during the parlour observation of individual cows participating in the study by using milk yields at the end and start of the second minute of milking.

Table 3.4: Summary of the second minute milk flow (kg/min), for the three switch-point settings

	Switch-point settings		
	0.504 kg/min	**0.630 kg/min**	**0.840 kg/min**
Average	2.96	3.00	2.83
Median	2.85	2.90	2.90
Min	0.20	0.20	0.20
Max	8.50	7.50	7.90
SD	1.40	1.21	1.23
Number observation used	324	309	307

The milking preparation was evaluated and the latency period timed.

Table 3.5: Summary of the latency period (min), for the three switch-point settings

	Switch-point settings		
	0.504 kg/min	**0.630 kg/min**	**0.840 kg/min**
Average	1.57	2.41	2.19
Median	2.00	3.00	2.00
SD	0.57	1.08	1.20
Number observation	315	315	313

The Shapiro test indicated that the distribution was not normal for any of the variables tested. The ARC switch-point settings of 0.840 kg/min, 0.630 kg/min and 0.504 kg/min were compared for the following variables: machine-on time, overmilking duration, total vacuum, vacuum at peak flow and vacuum during overmilking. The Kruskal-Wallis test indicated significant differences ($p < 0.05$ or $p < 0.001$), between switch-point settings expected for the machine-on time (Table 3.6). However, when the differences between each switch-point setting were compared separately using the Wilcoxon test, the machine-on time showed no significant differences for 0.840 kg/min versus 0.630 kg/min and for 0.840 kg/min versus 0.504 kg/min (Table 3.6). In the case of the comparison of mean vacuum at peak flow versus mean vacuum at overmilking for the three switch-point settings only the Wilcoxon test could be used (Table 3.7)

There were 315 VaDia readings for each of the three switch-point settings available for analysis. Of these readings 14.9%, 12.7% and 11.1% were not used in the final data set for the 0.840 kg/min, 0.630 kg/min and 0.504 kg/min settings respectively. Reasons for exclusion of these results were in 65 cases incomplete VaDia readings; in 27 cases the milking routine was compromised (cluster reattachment, kick-offs and liner slips) and 30 readings were from cows that were not included in the trial. The average latency period measured in this study in the parlour was 120 sec and varied between 60 sec and 240 sec.

Table 3.6: Comparison of the different variables measured by the VaDia for the three switch-point settings

Variable	ACR switch-point (kg/min)	Mean	Minimum	Maximum	Kruskal-Wallis rank test p-value	Wilcoxon test p-values		
						0.840 vs 0.630 (kg/min)	0.840 vs 0.504 (kg/min)	0.630 vs 0.504 (kg/min)
Machine-on time (sec)	0.840	290.0^a	175.0	670.0	0.035*	0.685	0.072	0.010*
	0.630	289.2^a	184.0	858.0				
	0.504	303.3^b	195.0	936.0				
Overmilking duration (sec)	0.840	76.5	1.0	389.0	<0.0001*	<0.0001 **	<0.0001 **	0.325
	0.630	103.9	0	323.0				
	0.504	108.2	1.0	367.0				
Mean total vacuum (kPa)	0.840	28.2	12.7	35.0	<0.0001*	<0.0001**	<0.0001**	0.326
	0.630	31.2	17.7	43.0				
	0.504	31.0	18.6	36.4				
Mean vacuum during peak flow (kPa)	0.840	28.1	12.2	35.6	<0.0001*	<0.0001**	<0.0001**	0.115
	0.630	31.6	16.5	42.8				
	0.504	31.0	16.5	36.2				
Mean vacuum during overmilking (kPa)	0.840	28.6	10.7	36.4	<0.0001*	<0.0001**	<0.0001**	0.569
	0.630	32.9	13.6	43.9				
	0.504	32.3	13.2	37.5				
						<0.0001 **	<0.0001 **	<0.0001 **

In the Wilcoxon and Kruskal-Wallis tests the p-values that differ significantlyat levels $p < 0.05$ and $p < 0.001$ are indicated by *, ** and *** respectively.

Table 3.7: Comparison of mean vacuum at peak flow versus mean vacuum at overmilking measured by the VaDia for the three switch-point settings

Switch-point settings	Wilcoxon test p-values
0.840 kg/min	<0.0001
0.630 kg/min	<0.0001
0.504 kg/min	<0.0001

The p-values differ significantly at $p < 0.0001$ level of significance.

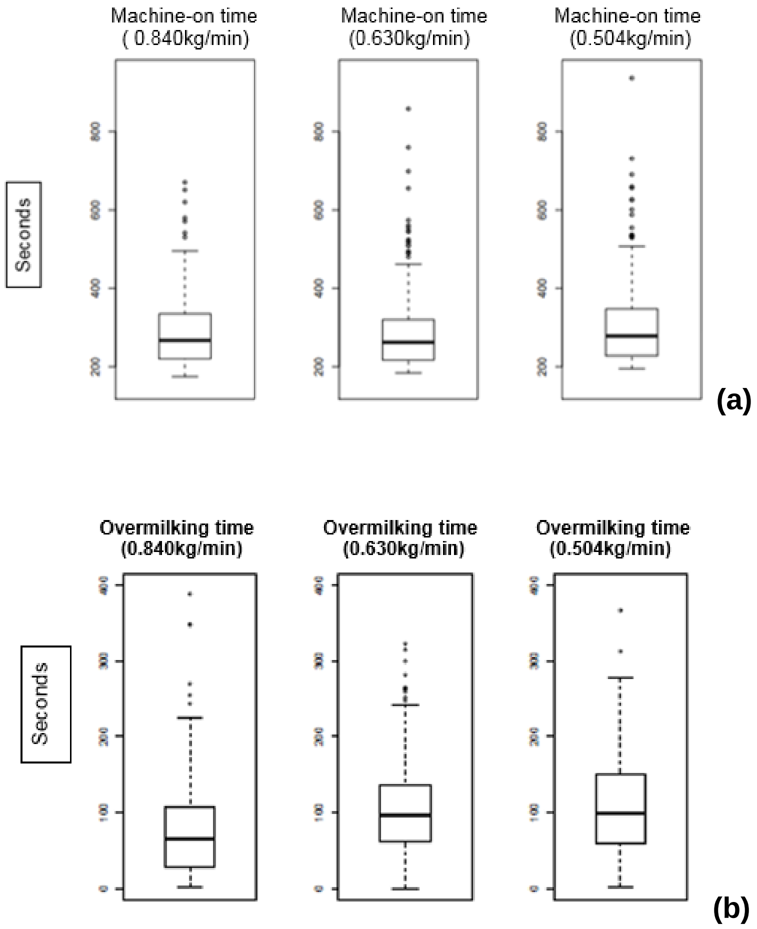


Figure 3.2: Machine-on (a) and overmilking time (b) at automated cluster removal switch point settings of 0.804kg/min, 0.630 kg/min and 0.504kg/min

The boxplots display the distribution of machine-on time and overmilking time for five values namely the median, minimum, maximum, the first quartile and third quartile.

3.4 Discussion

The teat size was determined for the study herd (Table 3.1; Table 3.2 and Figure 3.3). The average size of the front teats was larger than that of rear teats, especially in terms of the length of teats (Table 3.1). As far as teat size distribution was concerned (Ovesen, 1972), 40% of cows in the herd had average teat length (48.9 mm) and width (25.0 mm). Of the teats examined 11% were 30.0 mm or less in length. There were 12% of teats that exceeded a length of 70.0 mm (Table 3.2 and Figure 3.3). Liners with a barrel width of 23 cm were selected for this herd, based on the findings indicated in Figure 3.3, in order to achieve a proper liner fit in this herd. The correct liner fit is a critical component of practical liner application (Ohnstad and Reinemann, 2017) and aids in effective measurements when a Vadia instrument is used.

Cow behaviour during the complete milking which could have had an effect on the factors compared at different switch-point settings (Rasmussen, 1993) was shown in Table 3.3. This included reasons for exclusion of data such as, wrong cows milked, incomplete data for the cow, liner slip, kicking at the end of milking, vacuum failure (fall-off), leaking of VaDia pipes and clinical mastitis (Table 3.3). During all three switch-point trials liner slip, although present in less than 5% of cases, contributed the most (33.8%) to exclusion of data while incomplete data and incorrect cows contributed 34.6% to the exclusions. Clinical mastitis in study animals was evident in 1.5% of exclusions.

Other parlour observations noted (Rasmussen, 1993), were the number of uncomfortable cows at the end of milking (shifting weight) and a ring formation or slight swelling visible at the base of the teat after cluster removal (Table 3.3). When kicking and weight shifting just prior to machine take-off and teat swelling were combined, most reactions to pain (26 cows) were noted when the 0.630 kg/min switch-point setting was used compared with the least (3 cows) during the 0.840 kg/min setting. The same trend for the switch-point setting was evident in teat swelling and teat base rings post milking (Table 3.3).

The anatomy and functional characteristics of the teat can affect milk flow performance considerably (Weiss et al., 2004). Second minute milk flow (Table 3.4) could have had an effect on the factors compared at different switch-point settings (Table 3.6) and on teat size which was determined (Table 3.2). Wieland et al., (2017) found that teat-end shape was linked with milking characteristics such as second minute milk yield, machine-on time, and flow rate. The results in this study did not indicate major difference in the second minute milk flow between the three settings (Table 3.4).

Vetter *et al*. (2014) found that teat preparation consisting of a short stimulation followed by a latency period (Table 3.5) represents a similarly efficient pre-stimulation as a continuous pre-stimulation. For all three switch-point settings used, the average latency periods were greater than 1.5 min (Table 3.5), which is considered to be an acceptable latency period (Vetter *et al*., 2014).

Automated cluster removal switch-point adjustments should only be made when other machine settings are already in place and functioning optimally (Stewart *et al*., 2002) as many settings vary amongst different milking systems changing any settings should be done in conjunction with system specialists. Stewart *et al*. (2002) suggested that ACR switch-point settings should be changed in small gradual increments and monitored carefully for the response. Stewart *et al*. (2002) recommended that switch-point settings should be raised by increments of only 0.09 kg/min to 0.14 kg/min per adjustment.

3.4.1 Machine-on time

Studies, including the current study, agree that when the switch-point settings increase, machine-on time decrease (Besier and Bruckmaier, 2016; Boloña *et al*., 2020; Maliagro and Kensinger, 2005; Rasmussen, 1993; Sagi, 1978). Machine-on time decreased significantly ($p < 0.05$) in the current study by 4.65%when the switch-point setting was increased from 0.504 kg/min to 0.630 kg/min. There was however little difference in machine-on time between 0.630 kg/min and 0.840 kg/min (Table 3.6). The boxplots in Figure 3.2a indicated that there was more variation in the data during the longer machine on times, i.e. percentage differences of maximum and mean machine-on times for the three switch-point settings (0.504 kg/min, 0.630 kg/min and 0.840 kg/min) were 67.6 %, 66.3 % and 56.7 % while for the same settings the minimum and mean times differed by 35.7 %; 36.4 % and 39.7% respectively, from the mean values. When the ACR switch-point settings approached their optimal setting for the parlour, the less improvement will be noticed in machine-on time (Magliaro and Kensinger, 2005). The most significant improvements are seen when settings are changed from a relatively low switch-point to a higher switch-point (Magliaro and Kensinger, 2005). These results suggested that a setting of 0.630 kg/min was approaching the optimal machine-on time for the test herd.

Machine-on times cannot be directly compared between studies as there are differences in milking equipment, herd milk yield, frequency of milkings, machine settings and different milking systems that may be used (Besier and Bruckmaier 2016; Boloňa 2020; Maliagro and Kensinger, 2005). This emphasises the importance of the investigation of switch-point settings on an individual farm basis where factors such as milking frequency, parlour design, degree of milk ejection reflex, vacuum and pulsation settings and cow grouping form part of the measurement. The machine-on time depends on milk yield, stage of lactation and parity (Ginsberg *et al*., 2018).

The study by Maliagro and Kensinger (2005) differed from the current study in the number of areas, the herd was milked twice daily and not three times, the milking (system) vacuum was higher at 45.4 kPa and different switch-points were tested. Magliaro and Kensinger (2005) however found the mean machine-on time between their three switch-points to be 354.0 sec compared to 297.1 sec found in this study. Stewart *et al*. (2002) found a reduction of machine-on time between 10.2 sec and 15.6 sec per cow with increased ACR switch-point settings with a significant increase in milk flow. The estimated increase in milk flow between 0.05 kg/min to 0.19 kg/min across the five study herds increased with increased switch-point settings (Stewart *et al*., 2002). This was expected as clusters were removed earlier which resulted in less time spent in 'low flow' but milk yield would remain constant (Stewart *et al*., 2002).

Reduced machine-on time may provide health and economic benefits to cows, as it can improve teat condition and udder health (Neijenhuis *et al*., 2000) and shorten the overall milking time to save on labour. This also lowers the risk of teat canal damage without negatively affecting milk production, milk component yields, or udder health because of a reduction in overmilking duration (Wieland *et al*., 2020).

3.4.2 Overmilking duration

The liner mouthpiece forms a seal at the base of the teat which constricts the annular ring and delays milk flow between the gland and teat cistern when overmilking duration increases (Borkhus and Rønningen, 2003). This results in the inadequate removal of blood and interstitial fluids which leads to congestion and oedema of the teat (Ginsberg *et al*., 2018; Tanćin *et al*., 2006; Wieland *et al*., 2018). When little or no milk is being removed which is mostly seen towards the end of milking, the quarter is subjected to a higher vacuum, which leads to tissue stress (Ginsberg *et al*., 2018). In addition, milking efficiency decreases due to longer milking times (Ginsberg *et al*., 2018). Overmilking can be reduced by decreasing machine-on time and thus improving milking efficiency (Moore-Foster *et al*., 2019c).

This study found a significant ($p < 0.0001$) decrease in overmilking duration from the 0.630 kg/min to the 0.840 kg/min switch-point settings of 27.4 sec (Table 3.6 The minimum overmilking durations ($p < 0.0001$) varied more significantly from the mean values for all ACR settings than those of the minimum and mean machine-on times ($p < 0.05$) (Table 3.6 Figure 3.2b). Overmilking duration, as a percentage of total machine-on time, decreased from 35.67% (at 0.504 kg/min) to 35.93% (at 0.630 kg/min) and 26.38% (at 0.840 kg/min) respectively. These findings agree that increased overmilking is correlated with increased milking duration and thus decreasing milking and parlour efficiency (Moore-Foster *et al*., 2019c). Ginsberg *et al*. (2018) stated that overmilking is more likely to occur at low (0.200 kg/min) switch-point settings, depending on milk flow.

Recent studies have placed more emphasis on quarter milk flow patterns. The latter provide more biological information needed to improve milking machine settings (Tančin *et al*., 2007) using milk flow patterns. When flow of the switch-point volume is determined using udder instead of individual quarter milk flow, overmilking duration of the fastest quarter will be extended, as the cluster will remain attached until the udder milk flow reaches the switch-point. In a study by Boloña *et al*. (2020) overmilking duration at quarter level was ranked according to within-udder duration. The fastest milking quarter in that study, had an overmilking duration close to 2.0 min compared to 0.5 min in the slowest quarter at a 0.200 kg/min ACR switch-point setting. Ginsberg *et al*. (2018) found that rear teats are overmilked at a lower switch-point than front teats when take-off milk flow is based on udder milk flow. Hind quarters not only produce more milk, but also have longer increase, plateau and decrease milk flow phases (Tančin*et al*., 2006). Ginsberg *et al*. (2018) stated that the length of the decline phase depends largely on how close the teat end is to the flow meter. Swing-over parlours are especially affected by this as flow meters tend to be far away from the teat end (I.M. Petzer, personal communication, May, 2019). The decline phase is also affected by parity and Ginsberg *et al*. (2018) found that it was 125 sec for first lactation cows and 159 sec for older cows at the udder level and 57 sec and 66 sec respectively, at the quarter level.

Overmilking of the quarters with lower milk yield can lead to higher SCC, which may negatively influence the health of such quarters (Tančin*et al*., 2007). Tančin *et al*. (2007) found that quarters with high SCC ($>500\times10^3$ cells/ml) had lower peak milk flow rates and longer overmilking durations in comparison to quarters with lower SCC ($>200\times10^3$ cells/ml). Moore-Foster *et al*. (2019a) achieved a median overmilking duration of 47 sec and a mean overmilking duration of at least 30 sec.

3.4.3 Mean total claw vacuum

In order for the cluster to function optimally it is important to maintain stable claw vacuum inside the liner through the entire milking (Ambord and Bruckmaier, 2010). However, in high milk-line milking systems, high milk flow causes a loss of vacuum inside the milk tube (Ambord and Bruckmaier, 2010). Nevertheless, if vacuum is too low it may cause the claw vacuum to reverse during the a-phase of pulsation, risking reflux of milk back from the claw to the teat tip or into the udder (Ambord and Bruckmaier 2010). This reverse reflux of claw vacuum when the liner is open may lead to cross infections between quarters and may damage teat canals.

This study found that the mean total claw vacuum decreased significantly (p <0.0001) from 31.2 kPa to 28.2 kPa, when the switch-point level was raised from 0.630 kg/min to 0.840 kg/min (Table 3.6. This finding is in general agreement with those of Besier and Bruckmaier (2016) that concluded that a high milking (system) vacuum compensates for a non-avoidable vacuum drop allowing for good milking performance. However, the latter increases the risk of negative effects on the teat end, but this risk can be lessened by increasing the ACR switch-point settings (Besier and Bruckmaier, 2016).

Rasmussen and Madsen (2000) compared vacuums in high and low milk line systems at peak milk flow. It was found that the average vacuum measured in the claw was 32.8 kPa for the high milk-lines at a system vacuum of 48 kPa versus 38.7 kPa claw vacuum for the low milk-line milking system at a system vacuum of 42 kPa. Rasmussen and Madsen (2000) recommended that the average claw vacuum should not be less than 32 kPa because low claw vacuum increases machine-on time and the frequency of liner slip. At the same time, it decreased milk flow rates with no significant changes in udder health and teat condition.

3.4.4 Mean peak flow claw vacuum

During the plateau phase of milking, the peak milk flow rate is reached. The plateau phase indicates restrictions either in the flow rate from the quarter to the teat cistern, flow rate through the teat canal or the flow rate out of the teat. The teat canal is regarded as the main barrier for high flow rates but liner vacuum, long milk hoses, milk-line height, pulsation rate and pulsation ratio are the mechanical barriers for high flow rates (Ginsberg *et al*., 2018). Ambord and Bruckmaier 2010 found that the vacuum drop in the claw during peak milk flow was 15 ± 0.7 kPa.

In this study, the mean claw vacuum at peak flow only decreased significantly (p<0.0001) from 31.6 kPa to 28.1 kPa when the switch-point setting of 0.630 kg/min was increased to 0.840 kg/min, but did not differ significantly between switch-point settings of 0.504 kg/min and 0.630 kg/min. Ginsberg *et al*. (2018) agreed that at higher switch-point levels milk flow increased and machine-on time decreased. Besier and Bruckmaier (2016) found that the minimum claw vacuum influenced milking performance as it decreased milk flow and caused longer milking times and recommended a minimum claw vacuum of above 30kPa. This is lower than the 28.1 kPa that was noticed in this study at a switch-point setting of 0.840 kg/min. Besier and Bruckmaier (2016) found that a claw vacuum below 30kPa as a result of a high vacuum drop during peak milk flow caused a reduction in milk flow with longer machine-on times. Therefore, a high system vacuum could compensate for the drop in claw vacuum allowing for good milking performance, but it increased the risk of teat congestion and damage. The optimal milking performance and teat condition can be attained, only if a reasonable vacuum drop occurs during peak milk flow (Besier and Bruckmaier, 2016).

3.4.5 Mean overmilking claw vacuum

Milk flow rate affects the claw vacuum especially at high flow rates. The vacuum in the claw will approach that of the system vacuum during overmilking (Rasmussen *et al*., 2006). Overmilking can take place at the start, during and at the end of milking. Any disruption of the cows (vacuum loss, mastitis and cluster re-attachment) during milking may have affected the milk let-down or the milk flow. According to Besier and Bruckmaier (2016) the system vacuum was not likely to have an effect on teat health at the start of milking unless pre-stimulation was not adequate and the milk flow was low or transiently interrupted before milk ejection occurred. Well-stimulated udders allow for an immediate increase in the milk flow after the start of milking, inducing a drop in claw vacuum (Besier and Bruckmaier, 2016). Cows were calmer during high switch-points with less kicking, mainly due to clusters being removed earlier with higher switch-point settings.

The current study found a significant decrease ($p < 0.0001$) in the mean overmilking claw vacuum of 4.3 kPa when the switch-point settings of 0.630 kg/min were raised to 0.840 kg/min (Table 3.6).

3.4.6 Comparison of mean vacuums at peak milk flow and during overmilking

The mean claw vacuum at peak flow and at overmilking differed significantly ($p < 0.0001$) for each of the switch-point settings but was higher with lower switch-point settings (Table 3.7). The difference between the peak and overmilking vacuum was 1.3 kPa at 0.504 kg/min and decreased to 0.5 kPa at the 0.840 kg/min setting, which indicated a lower potential risk of teat canal damage. No other published work could be found that compared the mean vacuums at peak flow and mean vacuum at overmilking between different ACR switch-point settings, thus making this information valuable.

In a study completed by Tančin *et al*. (2006) the duration of the decline milking phase is believed to be more important at quarter level if the physiological response of cow to milking is considered. This study found an increase in the duration of the decline phase in quarters with high peak flow rates and rear quarters especially at the beginning and end of lactation (Tančin *et al*., 2006). The reduction of milk flow nearing the end of milking reduces the chances to flush out pathogens, increasing the risk of IMI (Philpot and Nickerson, 1991; Tančin *et al*., 2006).

Boloña *et al*. (2020) found significant within-udder differences in overmilking duration between individual quarters reporting a reduction in overmilking duration of 1.28 min for the fastest milking quarter compared to 0.47 min for the slowest quarter. This means that when the switch-point is reached the fast milking quarters would contain less strip yield than the slow milking quarters (Boloña *et al*., 2020). At udder level, the end of the plateau phase is determined by the duration of the fastest milking quarter. At quarter level however, the end of the plateau phase is determined by the availability of the milk in that quarter (Weiss *et al*., 2004).

3.4.7 Limitations of the study

The ACR settings measured on quarter level provide more detailed data on overmilking on quarter level than udder level data. This data however is not yet practical to use in dairy parlour other than robotic farms where quarter milk flow is used to initiate cluster take-off. Measuring strip yield in future studies will also help determine the difference in milk yield between ACR switch-point settings.

3.5 Conclusion

Increasing switch-point settings to approach the optimal setting for the parlour and herd proved to be meaningful in order to obtain a balance between milking speeds and the preservation of teat integrity. Machine-on time decreased significantly by 4.65% when the switch-point volume was increased from 0.504 kg/min to 0.630 kg/min, but only marginally at a higher switch-point setting. This indicated that the optimal setting for this herd's machine-on time was between the 0.630 kg/min and 0.840 kg/min switch-point setting. The overmilking duration however shortened significantly by 27.4 sec when the setting of 0.630 kg/min was increased to 0.840 kg/min.

Mean total claw peak flow and overmilking vacuums all decreased significantly with 3.0 kPa, 3.5 kPa and 4.3 kPa respectively, when the switch-point levels were raised from 0.630 kg/min to 0.840 kg/min potentially lowering the risk of teat damage. In addition, it was found that the mean claw vacuum at peak flow and at overmilking differed significantly for all of the switch-point settings but decreased as the switch-point settings increased.

This study indicated that while machine-on time was decreased by 4.4%, the overmilking duration was 29.3% shorter and the vacuum during overmilking was 3.7 kPa lower when an ACR switch-point setting of 0.840 kg/min was used compared to 0.504 kg/min. The overmilking duration was 26.4% shorter and overmilking vacuum was 4.3 kPa lower, when an ACR switch-point setting of 0.840 kg/min was used compared to 0.630 kg/min.

It was concluded that the use of the correct ACR switch-point setting (0.840 kg/min) lowered the risk of teat end damage due to shortening machine on time and decreasing the overmilking duration and the vacuum level for the 10-point, low milk line, herring bone parlour used in this study.

The knowledge gained by this study can be applied on individual dairy farms with different parlours and milking machines, to optimise settings in order to obtain a balance between milking efficiency, udder health and cow comfort.

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Chapter 4

4.1 Dissertation summary

Effects of automatic cluster remover switch-point settings on milking performance and overmilking in dairy cows

The research completed in this study includes an extensive literature study regarding the effects of milking machines on udder health and knowledge on the physiological and technical background for change of switch-point settings. This knowledge is required in order to optimise switch-point settings for dairy parlours, but mainly for the numerous swing-over parlours present in South Africa. These parlours now required automated cluster removals for the large dairy herds. The goal of this study was to achieve gentler and complete milking methods as this will result in a higher milk yield, healthy cows and efficient milking routines. In the modern-day, automatic cluster removers (ACR) have led to significant udder health improvements, including reductions in overmilking, liner slip and machine-on time. However, there are still large differences in the ACR take-off settings and recommendations between literature studies. Economic pressure led to the installation of high milk-lines affecting milking efficiency and ACR settings, in South Africa. In high milk-lines the extended distance between the milk flow meter and the cow may cause delay in ACR take-off times.

The milking parlour of the experimental farm of the University of Pretoria was used to conduct the research. The parlour is a 10-unit Waikato herringbone system with a low milk line, ACR and Afimilk as the operating system. This study represents the liner types used within the industry of South Africa namely a round liner. The VaDia (BioControl, Norway) was used to determine and record the vacuum levels (indirect the milk flow) for the complete milking period. This was done at the mouth pieces (MPC) of both the front and hind teats, the hind teat short milk tube (SMT) and hind teat short pulsator tube simultaneously. To date there are no guidelines for the removal of milking clusters at specific milk flow thresholds, which results in large variation in recommendations for take-off settings between different milking equipment suppliers.

This study investigated the effect of three ACR switch-point settings on milking and overmilking duration and on the vacuum level during overmilking in relation to the total system vacuum. This was completed using a VaDia to record all the vacuums during the milking process, making it possible to determine how the ACR switch-point settings (0.840-, 0.630- and 0.504 -kg/min) influenced overmilking and machine-on time. Research currently lacks data utilizing ACR switch-point settings in different parlours.

Automatic cluster removers are set using milk flow rate. When a set threshold flow is reached, this initiates the milking cluster to detach from the udder, whether all four quarters are milked out or not. This is to prevent extended milking time which leads to overmilking, which in turn may cause teat oedema and hyperkeratosis and increases the risk of new IMI and mastitis. Machine-on time decreased by 4.65%when the switch-point volumes were increased from 0.504 kg/min to 0.630 kg/min.

Overmilking may lead to teat congestion and can either occur at the start of milking prior to milk let-down, during milking or at the end of milking when clusters are left on for too long. This study found a significant decrease ($p < 0.0001$) of 27.4 sec in overmilking duration when the switch point setting of 0.630 kg/min was increased to 0.840 kg/min.

Especially at high milk flow rate the claw vacuum will be lowered. The claw vacuum will approach that of the system vacuum during low milk flow as at the start of overmilking. This study found that the mean total claw vacuum decreased significantly ($p < 0.0001$) from 31.2 kPa to 28.2 kPa when the switch-point levels were raised from 0.630 kg/min to 0.840 kg/min, lowering the risk of teat end damage.

The peak milk flow rate is reached during the plateau phase of milking. The plateau phase indicates restrictions either in the flow rate from the quarter to the teat cistern, flow rate through the teat canal or the flow rate out of the teat. The teat canal is the main barrier for high flow rates but some mechanical barriers including milk-line height may also affect high flow rates. In this study the mean peak flow claw vacuum decreased significantly ($p < 0.0001$)from 31.6 kPa to 28.1 kPa when the switch-point settings increased from 0.630 kg/min to 0.840 kg/min.

Stable vacuum at the teat throughout the entire milking is crucial for the cluster to function optimally. In high milk-line milking systems however, high milk flow rates cause vacuum loss inside the milk tube. If the claw vacuum is too low, it may cause a reflux of milk inside the liner from the claw back to the teat tip or into the udder. This may damage the teat canal or lead to cross infections between quarters. Therefore, a higher system vacuum may compensate for the vacuum loss allowing for good milking performance if the ACR switch-point settings are increased and used accordingly. The current study found a significant decrease ($p < 0.0001$)in the mean overmilking claw vacuum of 4.3 kPa between switch-point settings of 0.630 kg/min and 0.840 kg/min.

4.2 Advantages of this study

One of the key outcomes of this study includes an application of the pro-active approach to improve udder health by improving ACR take-off times, through the identification of more effective ACR switch-point settings. This research will provide insight into efficiency of take-off settings and will pave the way for use in commercial dairy herds, mainly those with swing-over parlour layouts utilizing ACR.

Correct take-off settings will assist to maintain teat canal integrity and the primary immune system of the udder and in so doing, will assist to prevent mastitis and increase longevity of the cows. Milking equipment suppliers, dairy farm advisors and operators can use this advice to improve milking performance and quality. This research can assist dairy producers and veterinarians in changing factory default settings on automatic take-offs correctly in order to achieve effective milking with minimal teat canal damage. This study found that changing the ACR switch-point settings per individual farm basis may have potential benefits such as a decrease in machine-on time and overmilking.

4.3 Recommendations of this study

This study recommends testing of current ACR switch-point settings in dairy parlours in order to achieve optimised settings using the more sophisticated VaDia method. To achieve the optimal machine-on time the balance between system (milking) vacuum, b-phase length and take-off settings should be sought. In the literature studies it was clear that milking efficiency does not solely depend on machine-on time, but also on higher take-off thresholds at high milk flow rates.

4.4 Limitations of this research study

The ACR settings measured on quarter level provide more detail data on overmilking on quarter level than udder level data. This data however is not yet practical to use in dairy parlours other than robotic farms where quarter milk flow is used to initial cluster for take-off. Measuring strip yield in future studies will also help determine the difference in milk yield between ACR switch-point settings.

4.5 Future research envisaged

In future studies animal welfare additional factors such as rumination and parlour time could be measured and taken into consideration. Measuring milk yield and strip yield will aid in the determination of the economic effect of changes in switch-point settings. Measuring strip yield in future studies will also help to determine the difference in milk yield between different ACR switch-point settings, especially at higher ACR switch-point settings.

4.6 General conclusion

Increasing switch-point settings to approach the optimal setting for the parlour and herd proved to be meaningful in order to obtain a balance between milking speeds and preserving the teat integrity. This study indicated a significant decrease of machine-on time (4.65%) as the switch-point volumes were increased from 0.504 kg/min to 0.630 kg/min, with only a small decrease at a higher switch-point setting. These results indicated that the optimal switch-point settings for machine-on time were between 0.630 kg/min and 0.840 kg/min. However, the overmilking duration shortened significantly by 26.4 sec when the setting of 0.630 kg/min was increased to 0.840 kg/min.

Mean total claw, peak flow and overmilking vacuums all decreased significantly by 3 kPa, 3.5 kPa and 4.3 kPa respectively, when the switch-point levels were raised from 0.630 kg/min to 0.840 kg/min, potentially lowering the risk of teat damage. In addition, it was found that the mean claw vacuum at peak flow and at overmilking differed significantly for all of the switch-point settings but decreased as the switch-point settings increased.

This study indicated that while machine-on time was decreased by 4.4%, the overmilking duration was 29.3% shorter and the vacuum during overmilking was 3.7 kPa lower when an ACR switch-point setting of 0.840 kg/min was used compared to 0.504 kg/min. The overmilking duration was 26.4% shorter and overmilking vacuum was 4.3 kPa lower, when an ACR switch-point setting of 0.840 kg/min was used compared to 0.630 kg/min.

The knowledge gained from this study can be applied on individual dairy farms with different parlours and milking machines, to optimise settings in order to obtain a balance between milking efficiency, udder health and cow comfort.