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Invited review: Contribution of milk harvesting research to optimal interaction between biology and milking technology

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ABSTRACT

The broad focus of this review is on milk harvesting in machine-milked herds. With particular emphasis on: (1) milk secretion and storage dynamics in the udder, (2) milk ejection, (3) milk flow profiles and their effect on milking efficiency, (5) immunological activity and milking efficiency, (5) milking machine aspects of milk removal, and (6) the future potential of milking technology. Machine milking has evolved from its early mechanical beginnings into a technologically advanced, data-driven process that must balance speed, chosen completeness, and gentleness on teat tissue to support efficient milk removal and optimal udder health. This review summarizes the current understanding of milk harvesting from a physiological, mechanical, and managerial perspective and outlines the key factors shaping its future development. Fundamentally, milk harvesting is built upon a biological sequence involving milk synthesis, ejection, and removal. Milk synthesis occurs at the alveolar level and is influenced by local quarter-specific physiology. Milk ejection is driven by the oxytocin-mediated contraction of myoepithelial cells, a process sensitive to the degree of udder filling, familiarity with the milking environment, and cow–operator interactions. Milk flow profiles, shaped by these biological processes, provide crucial insights into milking efficiency and udder health outcomes. At the machine level, key variables include milking vacuum, pulsation characteristics, liner properties, and teatcup removal strategies. Optimal settings for each of these parameters depend on dynamic interactions with cow physiology and milking stage. Recent research highlights the need to consider these factors not in isolation but as part of an integrated milking system, where vacuum, pulsation, liner design, and timing of teatcup removal interact to affect milking speed, teat condition, and udder health. Automation of milking systems and indeed automated milking systems have driven a shift toward individualized milking at the quarter level, enabling more precise control of extraction timing and flow rate. The integration of real-time sensor data, machine learning, and adaptive milking parameters represents a major step forward in the optimization of milking systems. In the near future, distinctions between automated milking systems and conventional systems will become increasingly blurred, as both adopt automation and intelligent controls tailored to individual cows and quarters. This review also explores the role of immunological activity in shaping milking efficiency. Elevated SCC has been associated with altered milk flow curves and decreased productivity. There is emerging evidence suggesting that modern selection and management strategies may reduce the historical link between fast milking and mastitis risk. This relationship remains complex and context dependent. The detection and management of abnormal milk (supported by more advanced inline sensor systems) is expected to become a cornerstone of future milking technology. Looking forward, the drivers of change in milk harvesting will include labor availability, economic pressures, environmental concerns, animal health, and consumer expectations. A new era of biologically aware, data-informed, and precision-engineered milking systems is emerging. These systems will support the gentle, efficient removal of milk to a

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user-defined end point, tailored to each animal and each milking event.

Key words: machine milking, milk ejection, milk flow profiles, automatic milking systems, precision dairy

INTRODUCTION

Scope of This Review

The broad focus of this scoping review is on milk harvesting in machine-milked herds, with particular emphasis on: (1) milk secretion and storage dynamics in the udder, (2) milk ejection, (3) milk flow profiles and their effect on milking efficiency, (4) immunological activity and milking efficiency, (5) milking machine aspects of milk removal, and (6) the future potential of milking technology.

Goals of Milking

The domestication of milk-producing mammals and the use of milk products has been widespread among human populations throughout the past 10,000 yr (Stock and Wells, 2023). Cow milk represents about 81% of global milk production (FAO, 2023). It is estimated that more than 50% of dairy animals are still being milked by hand worldwide. From 1900 onwards, vacuum-operated milking machines have continued to replace hand milking, especially in industrialized countries. The widespread adoption of machine milking was accelerated by labor shortages after World War II and also by improved quality of the harvested milk compared with hand milking.

The basic goals of milking are essentially the same for all types of milking methods, including by hand, bucket milking, parlor milking, and automatic milking systems (**AMS**). Up until the 1990s, they were to milk animals as quickly, as comfortably, and as completely as possible at every milking. In recent years, however, the definition of "complete" has evolved. With the rise of precision technologies, the focus has shifted toward milking to a user-defined end point, one that balances yield, efficiency, and animal-level factors (e.g., udder fill, milking interval, teat condition, parity, breed, and stage of lactation), rather than aiming for maximum removal of available milk in every case (individualization of milking is discussed later in the section "Future Potential and Drivers of Change"). Regardless, all methods depend on triggering the milk ejection reflex through tactile teat stimulation and release of the neuropeptide hormone, oxytocin, into the bloodstream before and during the entire milking process. This process requires the willing cooperation of each animal to enter her milking position calmly, to stand quietly for milking, and to leave calmly without endangering the milking staff.

Since the early 1900s, 2 major revolutions have occurred:

1. The mechanization revolution of the 20th century. The mechanization of milking had an astonishing effect on labor productivity throughout the 20th century.
2. The information and automation revolution, which started in the 1970s. Ongoing developments in automation and information technology on farms will continue to transform the future of dairying.

The Mechanization Revolution: Transition from Trial and Error to Science-Based Progress

The conventional double-chambered teatcup (in which a flexible liner is opened and closed cyclically) evolved from a series of inventions described in detail elsewhere (Dodd and Hall, 1992). In brief, the earliest inventors and inventive activity were as follows:

- In Scotland, where William Murchland trialed vacuum-based milk extraction without pulsation in 1891. Struthers and Weir later patented the first 2-chambered teatcup in 1892. The first device described as a "pulsator" was patented by Alexander Shiels in 1895.
- In Australia, where Hartnett (in 1893) and Alexander Gillies (in 1902) patented improved teatcup designs.

As is made clear by Dodd and Hall (1992), all of these early inventors thought their new vacuum-operated machines emulated hand milking: that is, they believed their machines withdrew milk during the squeeze phase of pulsation. This misconception persisted for decades. It still persists today, although less commonly, even though single-chambered teatcups, which were in limited commercial use until about 1920, clearly demonstrated that milk could be withdrawn from teats by application of vacuum without pulsation.

Dairy animals have been milked with 2-chambered teatcups for most of the past 120 yr.

Why? Because practical experience had shown that milking with pulsation induced less congestion (i.e., less swelling) within teat tissues and milked more quickly and more comfortably than single-chambered teatcups (Neave, 1959). The biological basis for both quicker milking and reduced congestion was not clarified until 1981 (Williams et al., 1981).

Steady development continued for the first 50 yr solely because of the inventiveness of practical individuals, milking machine manufacturers and innovative farmers (Dodd and Hall, 1992). In summary, all of those early ideas and components of milking systems had to be evaluated by the traditional practice of trial and error. Scientific research played no real part in the mechanization of milking until the 1940s.

Perhaps the earliest significant scientific contribution was by Ely and Petersen (1941) in Minnesota, which suggested a physiological basis for the milk ejection reflex. In the 1950s, a clearer picture of the action of the teatcup evolved from cine X-ray studies in the UK (Ardran et al., 1958). Subsequently, a series of scientific studies on possible links among milking machines, milking management, and mastitis in Ireland (Nyhan and Cowhig, 1967) and the United Kingdom (Cousins et al., 1973; Thiel et al., 1973) provided the foundation for the development of practical, science-based, mastitis control programs in most major dairying nations. A reliable method to measure the key hormone inducing milk ejection, oxytocin, has existed only since the late 1970s. The first hormone profiles with frequent sampling during the course of milking were published at about the same time in the United States (Gorewit, 1979; Schams et al., 1979). Before that, understanding of the biology of milk ejection was based mainly on assumptions. Milk synthesis, secretion, and ejection have been main subjects of research for decades, and the basics are well understood.

The Information and Automation Revolution

The automation of milking, data processing, and herd management represents the dawn of the second revolution in milking. Unlike the mechanization revolution, the automation revolution was started by science rather than by trial and error.

The scientific seeds of automation were sown in the Netherlands. Electronic cow identification was pioneered by scientists at Wageningen in the mid-1970s (Rossing, 1976). Dutch scientists (e.g., Maatje and Rossing, 1976) explored detection of cows in heat, or of sick cows, using physiological variables that could be measured automatically, such as cow activity (as an indicator of estrus), milk temperature, and electrical conductivity of milk (as a screening test for mastitis).

The AMS were installed on commercial farms starting in 1992. The early acceptance of AMS in Western Europe was accelerated by a new generation of Dutch scientists (De Koning et al., 2002). The AMS typically allows cows to choose when to be milked, shifting milking from a fixed, operator-driven routine to a more cow-driven process. In fully automated batch systems, however, this freedom is reduced due to structured milking cycles. Regardless of the configuration, automatic milking is more than just a different method of extracting milk. It represents a fundamental change in dairy farming, where milking becomes a background operation rather than a central event. The defining features of AMS extend beyond automation alone. Technologies such as quarter-level milking and fully unattended operation have arguably had an even greater effect on system design, daily routines, and farm management. With the adoption of AMS, milking routines became less dependent on operator consistency, placing greater importance on cow-level adaptability and automated decision making. System parameters such as vacuum level, pulsation setting, milking interval, teatcup attachment order, and detachment thresholds must be optimized for individual cows or quarters to ensure efficient milk removal (André et al., 2010; Upton et al., 2019; Boloña et al., 2022).

METHODS

This scoping review was guided by the PRISMA-ScR framework where relevant. All articles relevant to the review objectives were eligible for inclusion, including peer-reviewed articles and conference proceedings. Articles were included if they related to one or more of the 6 focus areas: (1) milk secretion and storage dynamics in the udder, (2) milk ejection, (3) milk flow profiles and their effect on milking efficiency, (4) immunological activity and milking efficiency, (5) milking machine aspects of milk removal, and (6) the future potential of milking technology.

Relevant literature was identified and selected by the coauthors based on their expertise and familiarity with the field. Key databases (e.g., Scopus, Web of Science, PubMed) and gray literature were consulted. Data were charted manually by the lead author and synthesized in discussion with coauthors. For each source, key findings relevant to the review themes were extracted and organized under thematic headings. No structured coding framework or duplicate extraction process was used, given the narrative and integrative nature of this review. Findings were summarized thematically across the 6 focus areas.

This review does not aim to provide an exhaustive systematic synthesis but rather a broad overview of current knowledge and gaps.

MILK SECRETION AND STORAGE DYNAMICS IN THE UDDER

Milk Storage in the Mammary Gland Compartments

Mammary secretory cells continuously secrete milk, whereas milk removal by machine milking occurs periodically (Knight et al., 1994). Between milkings, milk is distributed between 2 main compartments, the cisternal and the alveolar milk fraction (Bruckmaier et al., 1994a; Knight et al., 1994). The cisternal fraction, located in the cisternal cavities of the teats and glands, and the

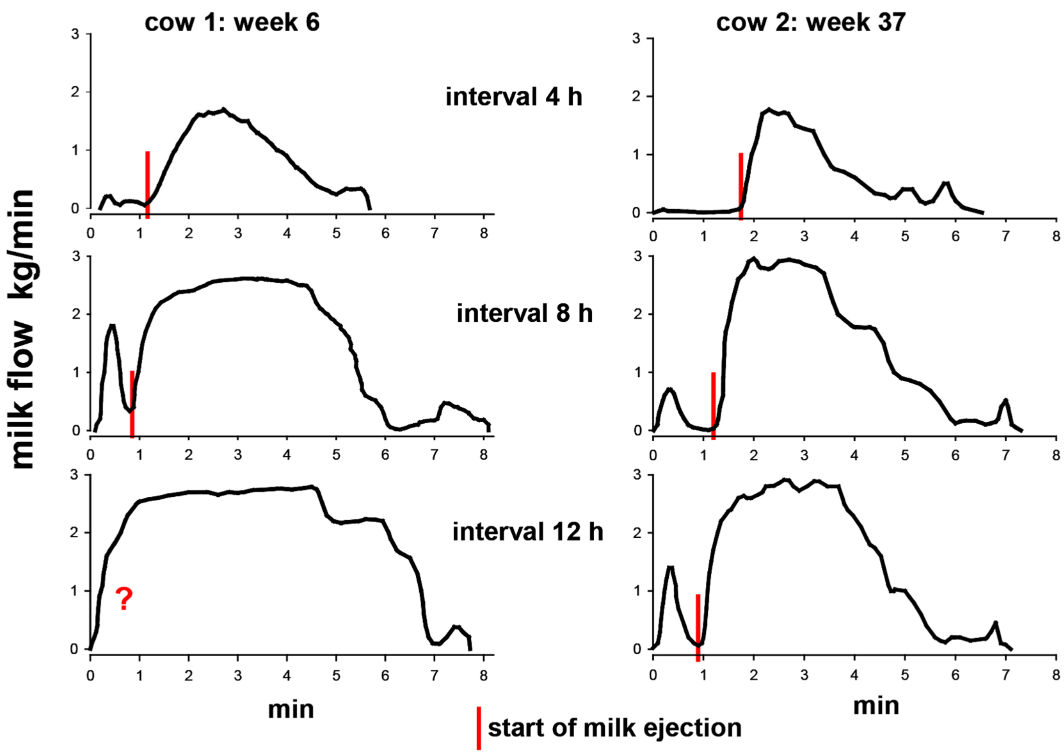

Figure 1. Start of milk ejection and resulting milk flow curves, influenced by stage of lactation and time since previous milking. Bimodal milk flow is evident at longer milking intervals due to the presence of cisternal milk, while shorter intervals result in unimodal flow due to limited cisternal reserve. Figure was adapted from Bruckmaier and Hilger (2001) with permission.

larger milk ducts, can be obtained by overcoming the teat sphincter barrier. Conversely, the alveolar milk fraction is retained by adhesive and capillary forces in the alveolar tissue due to the micrometer-scale diameter of the alveoli and the narrow milk ducts. Milk is continuously secreted by mammary epithelial cells into the alveolar lumen. Myoepithelial cells, specialized smooth muscle cells that surround the alveoli similar to baskets, contract in response to oxytocin release. This contraction drives the forceful movement of milk through the duct system into the cistern, a process known as milk ejection (Bruckmaier et al., 1994a). In 2 separate but complementary trials, Bruckmaier et al. (1994a) showed that the cisternal fraction can be up to 25% after an interval from previous milking of 10 to 12 h. The main influence on the cisternal fraction is the degree of udder filling, that is, the degree of alveolar fill which depends on the stage of lactation and the milking interval (Bruckmaier and Hilger, 2001). Knight et al. (1994) measured the cisternal and alveolar milk volume over the course of a 12-h milking interval and found that cisternal milk increased slowly during the first 4 h after milking and much more rapidly between 4 and 12 h after milking. In bimodal milk flow curves (when milk withdrawal occurs prematurely, before milk ejection), the cisternal milk fraction is represented by the first peak of the curve (see Figure 1; Bruckmaier and Hilger, 2001). In some cases, however, such as very short milking intervals, delayed milk ejection is no longer represented by a bimodal milk flow curve due to limited cisternal milk being present. Udder filling is driven by the interaction between milk synthesis rate and storage capacity. Although storage volume stays relatively constant, synthesis rate varies with lactation stage, influencing cisternal and alveolar fill. Older cows generally have larger cisternal fractions (Bruckmaier et al., 1994a; Pfeilsticker et al., 1996), allowing more passive filling as pressure from synthesis moves milk out of the alveoli and into the cisterns. Understanding the dynamic balance between these 2 compartments is critical for interpreting milk flow profiles (discussed later in the section "Milk Flow Profiles and Their Effect on Milking Efficiency") and optimizing milking system design.

The Pattern of Milk Constituents During the Course of Milk Removal

Several studies have examined how milk constituents change during milk removal. If quarter milk is divided into the following fractions: cisternal milk, alveolar milk 0% to 25%, 25% to 50%, 50% to 75%, 75% to

100%, and residual milk, a gradual increase of milk fat during milking with highest levels in the residual milk fraction can be observed (Ontsouka et al., 2003; Sarikaya et al., 2005). Recent studies showed that the secretion of milk fat globules out of the mammary epithelial cells is driven by myoepithelial contraction in response to oxytocin, which explains at least partially the increase during the course of milking (Hurtaud et al., 2020). A similar pattern to that of milk fat can be observed for the SCC, except for high levels of SCC in the cisternal fraction followed by lowest SCC in the first alveolar fraction (Ontsouka et al., 2003; Sarikaya et al., 2005). Milk protein and lactose are not subject to considerable changes during the course of milk harvesting. Both increase only slightly from the cisternal milk (strict foremilk) to the 0% to 25% alveolar milk fraction but then decrease again slightly over the course of milking (Ontsouka et al., 2003; Sarikaya et al., 2005).

MILK EJECTION

Neuroendocrine Control of Milk Ejection

Tactile stimulation of nerve ends primarily at the teat surfaces carries signals via the lumbar nerves to the supraoptic and paraventricular nuclei of the hypothalamus and to the posterior pituitary (Bruckmaier and Blum, 1998). Oxytocin is synthesized in these nuclei and stored in the posterior pituitary gland, the part of the pituitary which directly connects the central nervous system with peripheral circulation via the axons of oxytocinergic nerves. Therefore, oxytocin is released into the bloodstream within seconds of tactile teat stimulation and ultimately reaches the myoepithelial cells surrounding the alveoli to initiate contraction. Although this process begins rapidly, the route from the posterior pituitary to the udder is not direct. Oxytocin first enters the venous circulation, returns to the heart, passes through the lungs, back to the heart again, and is then pumped systemically to the mammary gland. This circulatory path likely contributes to the brief delay between teat stimulation and the onset of milk ejection. These myoepithelial cells then contract and expel milk stored in the alveoli into the milk duct system and further on to the cisternal cavities of gland and teat of each udder quarter (Bruckmaier and Blum, 1998).

Normal and Disturbed Oxytocin Release and Milk Ejection

Independent of oxytocin, the tone of smooth muscles around the milk ducts and in the teats, regulated by the sympathetic nervous system, is reduced before milk removal (readiness to be milked, sometimes causing milk leakage), which supports the movement of milk from the alveoli to the cisterns. However, the sympathetic tone and related rhythmic teat contractions increase between milkings and thereby contract the teat sphincter muscle, which helps to minimize milk leakage (Lefcourt, 1982).

Early findings of the half-life of oxytocin ranged from about 1 to 3.6 min (Gorewit et al., 1983). Gorewit et al. (1983) described the half-life by a 2-compartment exponential model revealing a fast and a slow clearance leading to a half-life of 3.9 min at a physiological level and 25.5 min if high amounts of oxytocin were injected. Also, continuously elevated levels of oxytocin throughout milking were detected at this time (Gorewit et al., 1983; Schams et al., 1984).

A significant experiment published by Bruckmaier et al. (1994b) proved that continuous elevation of oxytocin throughout milking was necessary for complete shift of alveolar milk into gland and teat cisternal compartments in parallel with milk removal. The experiment was carried out with cows with disturbed milk ejection and with cows in unfamiliar surroundings, causing central inhibition of oxytocin release. Cows were catheterized and received repeatedly small intravenous amounts of oxytocin during milking, which restored milk flow and facilitated complete udder emptying (Bruckmaier et al., 1994b).

Until 1941, the prevailing belief about milk ejection was that stimulation of nerves at teats and udder surfaces caused a direct contraction of the alveoli in the udder and then caused milk ejection. However, Ely and Petersen (1941) published a remarkable experiment where 5 cm of the ilio-inguinal and posterior inguinal nerves to one udder half of 3 cows was denervated. The 2 udder halves produced equal amounts of milk. Thus, Ely and Petersen (1941) proved that milk ejection was not under the control of a direct neuronal connection between the central nervous system and the mammary gland. Injections of posterior pituitary lobe extracts (= oxytocin) responded in milkings with normal milk yields from both udder halves. Frightening of cows before milking had the same effect on milk yield as an injection of adrenaline at a very high dosage, where only the cisternal milk was recovered. These early results also revealed that timing of frightening (or adrenaline injection) relative to onset of milking is important for the amount of extracted milk (Ely and Petersen, 1941).

Bruckmaier and Blum (1998) outlined the 2 pathways (peripheral and central) of disturbance of milk removal. Inhibition of milk ejection may be peripheral, including a normal release of oxytocin but with a lack of oxytocin response at the alveoli level. Wellnitz and Bruckmaier (2001) concluded that this has only been shown in pharmacological experiments. The practical implications of such a peripheral effect have never been confirmed. Leaving cows in a fight-or-flight mode after milk ejection will, however, reduce the blood flow to the udder, and the remaining part of the milking may be less efficient. Lack of oxytocin release from the pituitary gland is a consequence of central inhibition of milk ejection. Although central inhibition is often linked to environmental or emotional stress, peripheral factors such as teat pain caused, for example, by excessive teat-end vacuum levels or poor fitting liners, may also interfere with normal oxytocin-driven milk ejection (Bruckmaier, 2005). Bruckmaier and his group have carried out several experiments with milking cows in unfamiliar surroundings (Bruckmaier et al., 1994b; Bruckmaier and Blum, 1998), which resulted in lack of oxytocin release and only removing cisternal milk. Once the unfamiliar surroundings became familiar by repeated milking at the same location, the release of oxytocin normalized within only a few days (Bruckmaier and Blum, 1996). Unpredictable negative behavior by the milking operator such as harsh treatment of the animals was shown to increase the amount of residual milk by 70% (Rushen et al., 1999), whereas predictable negative behavior, even if unpleasant, had no effect on the milk yield harvested (Munksgaard et al., 2001).

These findings underscore the importance of consistent, low-stress handling to maintain optimal milk flow and minimize residual milk. Oxytocin release and effective milk ejection are highly sensitive to central inhibition triggered by handling or environmental stress. Calm, repeatable milking routines can help ensure complete milk removal and support animal welfare outcomes. Where needed, targeted milking-time observations may be helpful in identifying stress-related disruptions to milk ejection, provided they do not interfere with standard milking practices.

In emerging cow–calf contact (**CCC**) systems, recent summaries have highlighted potential issues with incomplete milk ejection and milk stasis during machine milking, which may relate to altered oxytocin dynamics or milking routine variability (Whalin et al., 2025). These observations raise important questions for future research regarding the physiological and management factors that support successful milk removal in CCC systems.

Timing of Prestimulation

Oxytocin release may be initiated by manual or mechanical prestimulation and leads to similar amounts of oxytocin in the bloodstream (Bruckmaier and Blum, 1996). In AMS, this premilking stimulation is typically achieved through mechanical cleaning devices, such as rotating brushes or teat wash cups. These devices serve a dual role: cleaning the teats and providing sufficient tactile stimulation to induce oxytocin release and initiate milk ejection. Different stimulation protocols exist depending on system design, including simultaneous brushing of all teats in multibox robots and sequential cleaning in single-stall configurations (De Koning et al., 2002; Mačuhová et al., 2003; Dzidic et al., 2004a,b). Time from stimulation until oxytocin release to the bloodstream and contraction of myoepithelial cells does not depend on stage of lactation and the udder fill (Kaskous and Bruckmaier, 2011). If the response is measured as time from stimulation until continuous milk flow, then this will be misinterpreted as long response time of late lactation cows compared with early stage of lactation. However, the amount of milk present in the cistern at the time of stimulation, influenced by udder fill and milking interval, can affect the latency between stimulation and observable milk flow (Bruckmaier and Hilger, 2001). For example, cows with a low cisternal milk fraction (e.g., due to short milking intervals) may show a longer delay before milk flow is initiated, despite normal oxytocin release. A short latency period of 30 to 60 s in between stimulation and cluster attachment makes the milking process more efficient (in terms of average milk flow rate [**AMF**]) for cows with an udder fill <40% (Kaskous and Bruckmaier, 2011). However, it has been demonstrated that a latency period of 2 min or more leads to a partial drop in maximum intracisternal pressure, due to rapid oxytocin clearance and reduced myoepithelial contraction (Bruckmaier et al., 1994b). By a new increase of oxytocin in response to new stimulation or cluster attachment, the highest intracisternal pressure is again reached. However, this secondary myoepithelial contraction acts on partially emptied alveoli, resulting in slower milk flow (Bruckmaier, 2001). During machine-on time, teat stimulation provided by liner movement helps maintain elevated oxytocin concentrations. A premature decline in oxytocin release, even in slow-milking cows, has never been confirmed.

Milking Management and Operator Effects

The objectives of premilking teat preparation are 3-fold: (1) clean the teat before cluster attachment; (2) detect abnormal milk; (3) provide tactile stimuli to initiate the milk ejection. Cow and teat cleanliness can have a significant effect on both milking efficiency and the rate of new mastitis infections. Cows that enter a milking facility with dirty teats require more preparation time, which reduces milking efficiency (Reneau and Chastain, 1995). Before cluster attachment, the teat needs to be visually clean, and soiled teats require greater operator input, which may reduce the number of cows milked per hour. However, this reduction in throughput may be offset by adjusting the milk flow threshold for automatic cluster detachment at the end of milking (Prendergast et al., 2025). Premilking teat stimulation induces the ejection of alveolar milk before the start of milking, thereby avoiding the interruption of milk flow after the removal of the cisternal milk. This can reduce the overall cups on time (Bruckmaier, 2001).

Examination of foremilk has been shown to effectively identify cows and quarters with abnormal milk. Failure of milking technicians to forestrip cows before milking has been demonstrated to have a significant negative effect on bacterial and SCC counts (Hellmuth, 1996). However, forestripping cows must be done in such a way as to minimize the spread of pathogens from cow to cow on milkers' hands.

As well as improving milking efficiency, reducing the environmental challenge to the teat-end in the cow environment has also been shown to reduce new mastitis infections. When cows were scored for udder hygiene on a scale of 1 (very clean) to 4 (very dirty), cows that scored 3 and 4 were 1.5 times more likely to have major pathogens isolated from milk samples compared with cows that scored 1 to 2 (Schreiner and Ruegg, 2003). These results reflect hygiene status in the cow's environment and do not account for the effectiveness of premilking preparation.

Numerous studies have examined the role of the type of disinfectant, duration and intensity of wiping, and the materials used for cleaning (Galton et al., 1986). There is significant evidence that the benefit of premilking teat disinfection is variable, with some studies stating a reduction in the incidence of mastitis (Pankey et al., 1987; Oliver et al., 1993a,b, 2001), and others stating no additional benefit of premilking teat disinfection when used in conjunction with postmilking disinfection (Williamson and Lacy-Hulbert, 2013; Morton et al., 2014; Gleeson et al., 2018). Premilking disinfectants are most effective in killing environmental and contagious pathogens but have limited effectiveness in reducing the viable population of thermoduric bacteria. This limited effectiveness highlights the importance of a physical removal process to reduce the level of thermoduric bacteria (if present on teat skin) in bulk tank milk (Bade et al., 2008).

A combination of effective teat cleaning and forestripping will normally provide sufficient stimulation for milk ejection. Additionally, 10 to 20 s of tactile stimulation is normally considered adequate to lead to milk ejection in Holstein dairy cows (Reneau and Chastain, 1995). Achieving adequate teat stimulation can be challenging in large dairy operations, where performance metrics often emphasize speed and throughput. In these settings, the time available for premilking preparation is limited, making it essential to strike a balance between sufficient stimulation and overall milking efficiency.

MILK FLOW PROFILES AND THEIR EFFECT ON MILKING EFFICIENCY

Advances in Milk Flow Rate and Their Practical Implications

Milking efficiency influences the time required to milk the herd, which in turn determines the requirement for labor input during milking (Prendergast et al., 2024a). Deming et al. (2018) reported that the 25% most efficient farms required 3 h less labor per cow per year than the 25% least efficient farms. Several factors influence milking efficiency, including milking technology, animal health, and milk flow dynamics (Boloña et al., 2020; Prendergast et al., 2024b; Uí Chearbhaill et al., 2024). Two aspects that play a significant role in the efficiency of milk ejection are the shape of milk flow profiles (i.e., plot of milk yield vs. time) and the effect of immunological activity, particularly measured by somatic SCC.

Milk Flow Curve Phases

Milk flow profiles offer valuable insights into the milking process, as they reflect the rate of milk release from the udder during milking in an interplay with current milking machine settings. The flow of milk from the udder is broken down into the following phases (Bruckmaier et al., 1995; Tančin et al., 2006; Stauffer et al., 2020). These phases are visualized in Figure 2:

- Incline phase: The milk flow rate increases rapidly until it reaches a plateau.
- Plateau phase: Milk flows at a stable, high rate. During this period, milk from the alveoli, where the majority of milk is stored, is released. The peak flow rate (**PFR**) period is identified as the highest milk flow rate event of the plateau phase.
- Decline phase: The decline phase occurs as milk flow begins to decrease after most of the milk has been extracted. This phase continues until the flow rate drops below a threshold, signaling that the udder is approximately empty. In many cases, the cessation of milk flow does not occur simultaneously across quarters. This asynchronous behavior can be detected in udder milk flow curves as separate inflection points or stepwise reductions in flow, reflecting the individual quarters transitioning out of their peak milk flow periods.

Bimodal Milk Flow and Its Consequences

One phenomenon frequently encountered is bimodal milk flow, characterized by a period of reduction or even transient absence of milk flow in the early part of milking (Fernandes et al., 2023). Typically, bimodal profiles result from delayed milk ejection due to suboptimal stimulation or lag time of the cow before milking (Bruckmaier and Blum, 1998). The first peak usually represents the release of cisternal milk, while the second peak, often delayed, is due to alveolar milk flow, triggered later by the movement of alveolar milk to the teat cistern and si-

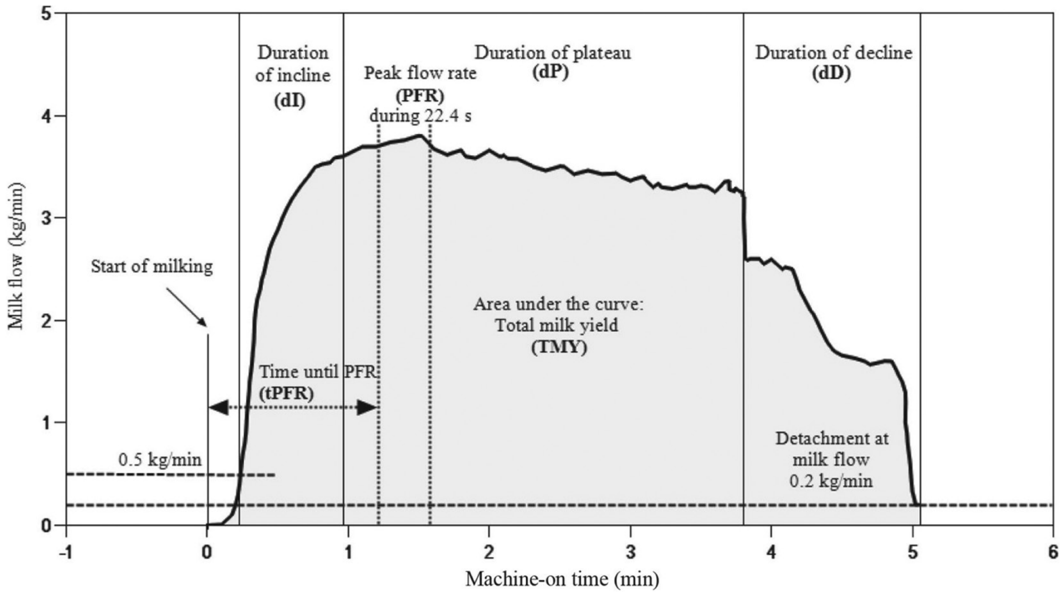

Figure 2. Example milk flow curve of an individual cow milked at low vacuum without vacuum reduction during low milk flow and at a detachment level of 0.2 kg/min, from Stauffer et al. (2020).

nus (Bruckmaier and Blum, 1998). This bimodal pattern can reduce milking efficiency by prolonging machine-on time (Bruckmaier and Blum, 1996; Fernandes et al., 2023). Although it has been speculated that bimodality may affect teat health under certain conditions, recent studies have not confirmed a consistent association with teat-end condition or mastitis. In the study by Fernandes et al. (2023), no correlations were detected between the proportion of cows exhibiting hyperkeratosis and farms' median overmilking time or the proportion of cows with bimodal milk flow. Similarly, Zecconi et al. (2018) observed a reduction in bimodal milk flow following treatment of mastitic cows with a nonsteroidal anti-inflammatory drug, but a causal link between bimodality and udder health has not been established. Risk factors for bimodal milk flow documented in the literature include level of udder fill, breed, stage of lactation, teat morphology, chronic mastitis infections, and health and management events (Dodenhoff et al., 1999; Bruckmaier and Hilger, 2001; Wieland et al., 2022; Wieland et al., 2024). Effective prestimulation and sufficient lag time can help initiate oxytocin release sooner, creating a single, continuous flow and thereby eliminating the bimodal pattern (Weiss and Bruckmaier, 2005).

Quarter Level Variability and Cluster Detachment

The differences in milk flow between quarters play a role in cow milking efficiency. In conventional milking, all quarters are milked with the same unit, and milking is stopped for all quarters simultaneously. Weiss et al. (2004) reported that the end of the plateau phase at the quarter level was determined by the presence of milk left to be extracted in the quarter, whereas the end of the plateau phase at the udder level was determined by the length of the plateau phase in the fastest milking quarter. The decline phase of the udder lasted until cessation of milk flow rate in the slowest milking quarter (Weiss et al., 2004), therefore, some quarters have been completely milked and are being overmilked by the time the cluster is detached (Boloña et al., 2021). Quarters within an udder have individual characteristics that influence the milking of the cow (Tančin et al., 2006). These correspond to anatomical and functional characteristics that can have a considerable effect on the milking performance of the quarter and cow (Weiss et al., 2004). Milk synthesis is highly regulated at the local level (quarter level), with systemic hormones largely uninvolved (Weaver and Hernandez, 2016).

In AMS, milking is conducted at the quarter level, which reduces overmilking (Hovinen and Pyörälä, 2011). Individual quarter teatcup attachment can increment the time from the first to the last teatcup attached compared with conventional milking (Gygax et al., 2007), and this could lead to large differences in end of milking times between quarters, which can affect milking efficiency. By understanding and analyzing milk flow profiles, dairy farmers can adjust stimulation techniques and milking routines, optimizing the process for both milking efficiency and cow comfort. Moreover, the availability of quarter-level milk flow data through AMS platforms now enables even more targeted adjustments to milking parameters. This creates new opportunities to manage milking practices at the quarter level, with the potential to improve milking efficiency (Boloña et al., 2022).

Immunological Activity and Milking Efficiency

The immunological health of cows is another important factor affecting milking efficiency. Elevated SCC (i.e., >200,000 cells/mL) correlate with decreased milk yield (Schukken et al., 2003; Sandrucci et al., 2007) and altered milk composition (Bansal et al., 2005). In a study by Tančin et al. (2007), quarters with elevated SCC exhibited a longer duration in the decline phase of milk flow, suggesting a negative effect on milking efficiency, although this was not noted at the udder level, similar to Tamburini et al. (2010), who reported that the duration of incline and decline phases was not significantly different among udder health categories. Furthermore, cows with elevated SCC were reported to have a shorter duration of the plateau phase in comparison with the other cows (Mijić et al., 2005; Sandrucci et al., 2007; Tančin et al., 2007). Work by Dodd and Neave (1951) found a correlation between udder milking rate (kg/min) and the incidence of mastitis in primiparous cows, presumed to be the result of larger diameter teat canals that provide less defense against bacterial invasion. Grindal and Hillerton (1991) used an experimental challenge with *Streptococcus agalactiae* and *Streptococcus dysgalactiae* and reported a significant increase in new cases of clinical mastitis when quarter PFR was greater than 1.6 kg/min. Conversely, large sample studies in the United States by both Brown et al. (1986) and Halley et al. (2001) reported that udder level PFR had no association with linear SCC. A retrospective case-control study in an AMS herd by Penry et al. (2017a) provided strong evidence that while milking interval was associated with the risk of clinical mastitis, the PFR of quarters was not. It is likely that intensive genetic selection of cows for high yield, fast milking, and low SCC has improved the defense mechanisms of the teat canal so that fast-milking cows are no longer at higher risk of mastitis. A recent study by Jin et al. (2024) demonstrated that machine learning algorithms analyzing milk flow profiles from previous milkings can successfully predict cows with elevated SCC in subsequent milkings, highlighting the potential of milking machine–derived data for early detection of udder health issues.

MILKING MACHINE ASPECTS OF MILK REMOVAL

Since the introduction of liner movement, or pulsation, the search continues for the optimum combination of milking vacuum level, pulsation settings, as well as liner properties and dimensions, to balance among milking quickly, completely, and gently. The introduction of automation added settings for teatcup removal to this trio. The review of research on vacuum, overmilking, teat condition, and udder health by Besier et al. (2016) noted that the scientific proof of the effects of vacuum stability and overmilking on udder health is scarce, with most of the literature published between 1960 and 1990. The authors go on to state that experimental methods, milking machines, and cows used for these experiments have changed and conclude that it is likely that similar investigations conducted today would show different results. In the last 30 yr, the milk yield per milking for high-producing Holstein cows milked 3 times per day has increased from 6.2 to 13.5 kg, AMF (or total yield/total cups on time) increased from 2.6 to 3 kg/min, and PFR has increased from 4 to 5 kg/min (Reinemann et al., 2025).

It is worth noting that various definitions of PFR and peak milk flow rate (**PMF**) exist in the literature, often depending on the resolution of milk flow data and the analysis method used. For example, Stauffer et al. (2020) defined PFR as the maximum flow rate maintained or exceeded for at least 22.4 s. Wieland et al. (2022) calculated PMF as the maximum 60 s average within the milking event. Other studies (e.g., Penry et al., 2017a) reported PMF values at the quarter level directly from AMS system outputs. The way that commercial milking systems report PFR is not consistent and is sometimes difficult to determine. These differences highlight the importance of considering methodological nuances when comparing PRF across studies. In most experimental contexts, PFR is used to evaluate relative changes in response to alterations in milking management or machine settings. Therefore, as long as the definition is clearly stated and appropriate for the criterion under investigation (e.g., udder or quarter-level analysis), a single standardized definition may not be required.

Milking Vacuum

Milking speed generally increases with increasing milking vacuum level. However, there are interactive effects of pulsation and liner compression (as measured by liner overpressure (**OP**), discussed later in "Pulsation Parameters"), so that this is not always the case. The collective wisdom of the scientific community produced the following guidance for setting vacuum levels in the International Organization for Standardization (**ISO**) standard for milking machine construction and performance: "Both research and field experience indicate that a mean liner vacuum within the range 32 kPa to 42 kPa during the peak flow period of milking for cows ensures that most cows will be milked quickly, gently and completely" (ISO, 2007, p. 14). This guidance for milking vacuum level was developed under the constraints of the physics of milk and air flow in the long milk tube, which creates a vacuum drop between the teat-end and the regulated milking system vacuum level. The teat-end vacuum is highest when there is little or no milk being removed, and lowest teat-end vacuum occurs when the milk removal rate is at its maximum. This relationship is linear and is affected primarily by the lift of milk from the teat to the milk line and, secondarily, by the restrictiveness of the flow path, which is influenced by the long milk tube diameter and length and by fittings and devices in the flow path (Mein and Reinemann, 2015). Every teat is exposed to high vacuum upon teatcup attachment, then is exposed to decreasing vacuum as the milk flow rate increases (with the lowest vacuum experienced by the fastest milking teats) and then higher vacuum again as the milk flow rate declines until the teatcup is removed. The vacuum drop, and hence milking vacuum difference, is increased for faster milking quarters and udders. This difference between the lowest vacuum at PFR and highest vacuum during low milk flow has increased alongside rising PFR in modern cows, thus creating increased need for strategies to care for teat tissues.

The ISO guidance is restricted to the PFR period of milking. Research has highlighted the importance of the milking vacuum level during the low-flow period of milking. Tuor et al. (2022) showed that milking speed continues to increase up to milking vacuum levels of 60 kPa, as long as the gland cistern remains sufficiently filled by continuous milk ejection. Stauffer et al. (2020) concluded that the negative effects of milking at high vacuum were prevented by using a low vacuum level during the low-flow period of milking. A review by Odorčić et al. (2019) provides compelling evidence that teat tissue congestion is produced during the low-flow period of milking because of elevated teat-end vacuum and primarily from elevated vacuum in the mouthpiece of the liner (Penry et al., 2017b; Odorcic et al., 2020). The maximum mouthpiece chamber vacuum is limited by the teat-end vacuum and is further reduced when an effective seal is created between the teat and the liner and, in some cases, by introduction of an air inlet to the mouthpiece chamber (Reinemann et al., 2013).

Vacuum Fluctuations

The ISO standards do not specify allowable values of vacuum fluctuation at the teat-end, in the claw, or in the mouthpiece of the liner. The purpose of measuring claw or short milk tube vacuum fluctuations is to find faults, such as plugged air vents, excessive air admission, or restrictions in the milk flow path. Some types of milking units intentionally incorporate large claw vacuum fluctuations as part of the normal pulsation cycles (NMC, 2012).

Research at the United Kingdom's National Institute for Research in Dairying in the 1970s showed an increase in new mastitis infections with the combination of high cyclic vacuum fluctuations (generated within the cluster by fast cyclic opening and closing of teatcup liners) together with high, experimentally induced, "irregular" vacuum fluctuations generated beyond the cluster (Cousins et al., 1973; Thiel et al., 1973). Later research in Ireland showed an effect of liner slips on new mastitis infection rate (O'Shea and O'Callaghan, 1978, 1987). The Irish cross-contamination "impact" mechanism was thought to result from vacuum fluctuations measured in the adjacent teatcups within an individual cluster when one teatcup slipped, typically under high bacterial-challenge experiments.

This mechanism was further investigated by Baxter et al. (1992), who reported a trend but no significant main effect between low slip (3.6 per milking) and high slip (6.1 per milking) liners on new mastitis infections in a herd with a new mastitis infection rate of about 9% of quarters infected per month. A post hoc analysis was done of cows entering the trial with and without an existing mastitis infection. They noted that the high slip liner group entered the study with a higher infection rate but did not indicate what this rate was. They reported that high slip liners had 0.42 more second quarter infections (of the same udder) per 100 cow days than low slip liners, which was not significant. However, bacterial analysis of the infection types eliminated the Irish cross-infection hypothesis as a causal mechanism in this case (transfer of pathogens from an infected quarter to an uninfected quarter). They thus concluded that only a small proportion of the new infections could have resulted from cross-infections. They concluded that uninfected quarters of cows with an existing quarter infection are apparently predisposed to new infections and that liner slips appeared to increase this infection risk. With a 10% prevalence of cows with 1 infected quarter, this amounts to a difference of about 1 new quarter infection per 100 cows per month.

The influence of vacuum fluctuations has thus changed over the past 50 yr. Although there never was any evidence that large cyclic fluctuations contributed to mastitis risk, the occurrence of the combination of large cyclic fluctuations with irregular fluctuations (liner slips) has been reduced considerably by cluster design. Larger claw volume and larger short and long milk tube diameters have reduced cyclic fluctuations. Liner design, lighter-weight clusters, and long milk tube support have reduced the occurrence of irregular fluctuations. This combination has virtually eliminated the conditions necessary for the hypothesis in modern milking systems. Furthermore, cluster designs that eliminate the possibility of cross contamination by impacts have been introduced but have never found widespread adoption, probably because they add mechanical complexity and the benefits in mastitis reduction have not been detectable on commercial farms. Total separation of quarters, as occurs in AMS, eliminates the possibility of the impact mechanism because in the rare case of a liner slip, the physical forces generated move milk away from the teat-end at a rapid speed. The vacuum fluctuations caused by slugging in the milk line are undetectable at the teat-end, and there is no plausible causal connection between this form of vacuum fluctuation and any measure of milking performance. A powerful study of over 7,000 milking-time tests on more than 1,000 Norwegian dairy farms found no association between irregular vacuum fluctuations and SCC on high-line, low-line, or AMS (Nørstebø et al., 2019). This 2019 study also found associations between higher short milk tube vacuum in the main milking period and lower SCC, longer duration of the main milking period and lower SCC, longer duration of the overmilking period and higher SCC in pipeline milking systems but not in parlors or AMS, higher mouth piece chamber vacuum in the main milking period, and higher SCC in pipeline systems but not parlor or AMS. Although association does not prove causation, if there is causation, one could expect association, and some causal effects can be ruled out or at least have an undetectable effect size given the power of the study.

Pulsation Parameters

In addition to being a biologically relevant indicator of liner compression, liner OP defines the point in the a- and c-phase of pulsation where milk flow starts and stops and defines the true milk/rest ratio (ratio of the pulsation cycle where milk is flowing; Leonardi et al., 2015). Note that the milk/rest ratio can differ substantially from both the pulsator ratio (percent of the pulsation cycle that the pulsator is “on”) and the pulsation ratio (a + b/a + b + c + d phases of pulsation; Reinemann, 2024). Milk flow rate increases linearly with the milk/rest ratio of pulsation, unless the change results in increased teat-end congestion (Penry et al., 2018). While it has been speculated that the duration of the c-phase of pulsation can influence cow comfort during milking, the only supporting evidence is a slight increase in milking speed when the c-phase duration was increased. This change in milking speed is entirely explained by the lengthened milk/rest ratio that results from extending the c-phase and does not support a cow comfort hypothesis (Reinemann, 2024). The ISO standards specify a minimum of 150 ms for the d-phase of pulsation (ISO, 2007). The validity of this specification was confirmed in a study (Upton et al., 2016), which also showed that there was no benefit for d-phase duration above 200 ms regardless of milking vacuum, liner OP, or the duration of the b-phase of pulsation. The effects of vacuum, pulsation, and liner compression are interactive, as discussed below.

Liner Properties and Teat-End Hyperkeratosis

The most important property of a liner is the fit between the liner and the teat. Good liner fit ensures a tight seal between the teat and liner barrel, as well as low mouthpiece chamber vacuum during the PFR period of milking. High mouthpiece chamber vacuum will result in teat barrel congestion, and this disruption in circulation will also result in congestion of teat-end tissues and slower milking. The liner property of second greatest importance is the degree of compression that the liner applies to the teat-end and the distribution of that pressure. Insufficient liner compression for a given vacuum and pulsation setting will result in teat-end congestion and slower milking (Penry et al., 2017b). Increasing liner compression will also increase the occurrence of teat-end hyperkeratosis (**TEHK**; Mein et al., 2003; Bade et al., 2007; Kochman, 2011).

Neijenhuis et al. (2001a) published a groundbreaking study in which they noted a small but significant association between teat-end callosity (i.e., TEHK) and clinical mastitis. This study ignited worldwide interest in teat conditions in addition to TEHK. A group of experts developed standardized methods for assessing teat condition, as well as guidelines for levels of concern for various machine-induced teat condition scores (Mein et al., 2001; Neijenhuis et al., 2001b; Reinemann et al., 2001). The work of Neijenhuis et al. (2001a) showed that the correlation between TEHK and mastitis risk is nonlinear, with the highest risk associated with no teat-end rings (**N**) and very rough (**VR**) teat-ends. Smooth (**S**) teat-end rings and slightly roughened (**R**) teat-ends had lower risk. Because of this nonlinear relationship, it is recommended that TEHK scores be assessed as categorical variables, not continuous numerical values (Reinemann et al., 2001). This advice has been widely ignored, and most published studies continue to use averaged numerical values. A systematic review of peer-reviewed studies on TEHK and mastitis risk was published by Pantoja et al. (2020). This systematic review found that: (1) teat scoring methods differed across studies, (2) the most frequent study limitation was improper use of statistical methods to avoid confounding associations, (3) only severe TEHK (VR) were associated with increased risk of clinical mastitis, subclinical mastitis, and SCC, and (4) mild TEHK (S and R) had lower mastitis risk than either N or VR scored teat-ends.

The review by Pantoja et al. (2020) indicated that the risk of mastitis infection appears to be about doubled for VR teat-ends compared with S and R scored teats, and about the same for VR and N scored teats. Consider the case of a herd with a new intramammary infection rate (**NIR**, defined as an increase in SCC above a threshold of 200,000 cells/mL for lactating cows between successive milk recordings) of 6 cases per 100 cows per month. This rate reflects the median monthly IMI rate reported for UK herds (AHDB, 2020). The NIR attributable to 10% of teat-ends scored as VR would be 6.6 cases per 100 cows per month. However, if the proportion of VR teats were reduced, it is likely that the proportion of N teats would increase. Given the similar risk associated with N and VR scores, the overall effect on NIR would likely be minimal.

It is also interesting to note that in the late 1990s and early 2000s, liners were designed for faster milking by increasing liner compression, resulting in increased prevalence of TEHK. Bade et al. (2007) reported a median value of 49% of R + VR teat-end scores, and Kochman (2011) a range from 13% to 47% of R + VR teat-ends, 2% to 12% VR teat-ends, and a high correlation between TEHK scores and liner overpressure. This is in marked contrast to a recent study (Reinemann et al., 2021) in which less than 3% of the 2,324 teats scored R + VR and 0.2% of teat-ends were scored VR. This dramatic reduction in the occurrence of VR TEHK virtually eliminates the association with mastitis risk and is the result of liner designs that use lower overpressure but more importantly, reduced stress concentration of teat-end skin. Although other factors have been shown to have a minor effect on the occurrence of TEHK, the predominant effect is the distribution of force of the collapsed liner on the teat end.

It is worth noting that none of the studies on TEHK and mastitis risk can conclude a causal relationship. This would require a controlled trial, where the hypothesized causal variable was randomly assigned to a treatment and control group of cows, while accounting for other known covariates for TEHK, such as teat length and shape. A plausible hypothesis explaining the nonlinear relationship between TEHK and mastitis risk is that the causal mechanism has more to do with the keratin dynamics of the inner lining of the teat canal than the rather different form of keratinization of the skin surrounding the exterior of the canal and that TEHK scores are associated with these causal effects. The ability of the teat canal to trap bacteria is reduced if a proportion of the teat lining is not flushed away during milking. Milking without pulsation in postmilking challenge experiments leads to an accumulation of keratin in the teat canal (Lacy-Hulbert et al., 1996), and very high new infection rates. A possible explanation for this is that keratin, potentially contaminated with pathogenic bacteria, is retained for longer in the teat canal, providing a greater opportunity for these bacteria to enter the gland (DairyNZ, 2012).

The reduction in mastitis risk for teats with S or R teat-ends compared with teats with N score may, therefore, be due to stimulation of keratin production on the interior lining of the teat canal in S and R teats, and not to the condition of the skin external to the canal. It is also possible that new liner designs that provide more uniform compression of the teat-end would provide the positive benefit of stimulating increased soft keratin production in the tissues lining the teat canal, while avoiding the stress concentration of the skin external to the teat orifice and reducing the production of teat-end rings. This might change the relationship between mastitis risk of teats scored N and those scored S, but this hypothesis awaits testing.

Teatcup Removal and Overmilking

Danish research on raising threshold settings for automatic cluster removers (**ACR**) provided the springboard for achieving shorter machine-on times and better teat-end conditions, especially in high-producing herds (Rasmussen, 1993). The combination of a preset maximum machine-on time plus an end point determined by a raised ACR milk flow threshold (whichever comes first) shortened machine-on times per herd by reducing or eliminating potential bottlenecks caused by slow-milking cows (Clarke et al., 2004). Increasing the ACR milk flow rate threshold for cluster removal from 0.2 to 1 kg/min was shown to reduce milking duration from 5.7 to 4.3 min (−1.4 min or 25%), while the overmilking of the slowest quarter was reduced from 2 to 0.7 min, strip yield of the slowest quarter increased from 0.2 to 0.66 kg (Boloña et al., 2020). The dramatic reduction in overmilking (and associated high mouthpiece chamber vacuum) accounts for the reduction in teat congestion observed in many studies in which earlier cluster removal was investigated. These studies also indicate that the increase in strip yield has not resulted in reduced milk production, nor has earlier teatcup removal had adverse effects on SCC or udder health (Ginsberg et al., 2018; Upton et al., 2023). However, the completeness of milking may have a stronger influence on milk yield in early lactation. Kuehnl et al. (2019) found that leaving 30% of milk in the gland during the first 6 wk postpartum caused a 27% reduction in milk production rate, which was not recovered even when cows were milked 3 times daily thereafter. This suggests that early lactation is a particularly sensitive window where incomplete milk removal can limit milk yield potential.

Interactions Among Vacuum, Pulsation, Liner Properties, and Teatcup Removal

Although it has been understood for some time that there are interactions among vacuum, pulsation, and liner compression on milking speed and teat tissue congestion, it is only recently that studies have been performed with the specific goal of quantifying these interactions (Penry et al., 2017b), rather than treating them as secondary points of interest, or not considering them at all. A simple example of an interaction is that the effect of increasing vacuum will be different for different pulsation settings, or for different liners. The example response surfaces (Penry et al., 2018) are for a low, medium, and a high OP liner, roughly spanning the compression range of commercial liners available on the market.

The effect of increasing milking (teat-end) vacuum from 32 to 50 kPa for a low versus high OP liner resulted in an ~30% increase in milking speed at the highest milk phase duration (Figure 3). The effect of increasing the milk phase duration from 300 to 800 ms resulted in an ~30% increase in milking speed. The effect of milking vacuum on milking speed ranges from 0% to a 30% increase, depending on liner OP and pulsation settings. Although the high OP liner can achieve the greatest milking speed, it is also likely to produce the highest levels of VR teat-ends (estimated at ~5% VR teat-ends). The medium OP liner controls teat-end congestion with very little increase in TEHK risk and allows milking speed to continue to increase as milking vacuum and milk phase duration increase with an estimated <2% level of VR teat-ends. The low OP liner is likely to produce the lowest level of VR teats ends (estimated at <1%), but this liner is unable to control teat-end congestion at high levels of vacuum and milk phase duration, and, as a result, is not able to milk as quickly under these conditions.

Thus, recommendations for milking conditions must take all 3 of these factors into account. In other words, one cannot make a recommendation about optimal milking vacuum levels without knowing pulsation settings and liner properties. It should be noted that these response surfaces are for the PFR period of milking. Another important consideration is the low-flow period of milking. The higher levels of milking vacuum can only be applied if the low-flow period is minimized by timely teatcup removal to minimize the low milk flow period.

The AMF for high-producing US Holstein herds in 1995 were ~2.6 kg/min at the udder level or 0.65 kg/min at the quarter level. Technological advancements have since increased quarter-level flow rates to ~1.5 kg/min in AMS, more than doubling milk removal speed over the past 30 yr, while simultaneously improving gentleness and completeness of milking (Reinemann et al., 2025). This improvement is the result of a combination of factors working in concert, including

- Optimized stimulation and lag time to ensure effective milk ejection at teatcup attachment;
- Adaptive milking intervals to reduce low-udder-fill milking events in automatic milking;
- Improved vacuum regulation that maintains higher teat-end vacuum during high-flow periods;
- Pulsation settings that avoid unnecessarily extended d-phase duration and increase the milk/rest ratio;
- Liner designs that relieve congestion without generating excessive mouthpiece chamber vacuum or TEHK;
- Earlier teatcup removal to reduce teat tissue stress during the low-flow period.

These advances are interdependent, none are sufficient in isolation. It is only the combination of all of them, facilitated by a sophisticated control system, that enables improved performance across all aspects of milking.

FUTURE POTENTIAL AND DRIVERS OF CHANGE

Milk production, now and into the future, is fundamentally about the efficient conversion of feed into milk. This process is grounded in the genetic potential of dairy animals, enabled by quality feeding and care, and sustained by the gentle and frequent removal of milk. Although the core principles of machine milking have remained relatively stable over time, the evolution of technology, management practices, and economic pressures suggest a dynamic future. Drivers of change are multifactorial and often region-specific. The diversity of milking systems that exist today reflects the industry's need for cost efficiency. Feed availability and associated costs will continue to determine where dairy farming is viable and will influence how cows are milked. In regions with feed constraints or rising costs, efficiency in milk harvesting becomes even more critical. The following outlook highlights key areas of expected development.

Social License for Milking: Creating a Positive Work Environment

The concept of creating a positive work environment for staff in modern businesses also applies to farming. The working-age children of dairy farming families, and their hired staff, are increasingly reluctant to commit to a life of milking cows 7 d per week and at both ends of every working day. An off-farm career involving a 9-to-5, 5-d working week is often seen as a more attractive option. Another current solution: the use of labor-hire teams (often hired from poorer nations) to do the repetitive work of milking large dairy herds, seems unlikely to meet longer-term criteria for "a social license to farm." Creating a positive work environment may be easier to achieve on dairy farms that have transitioned to AMS.

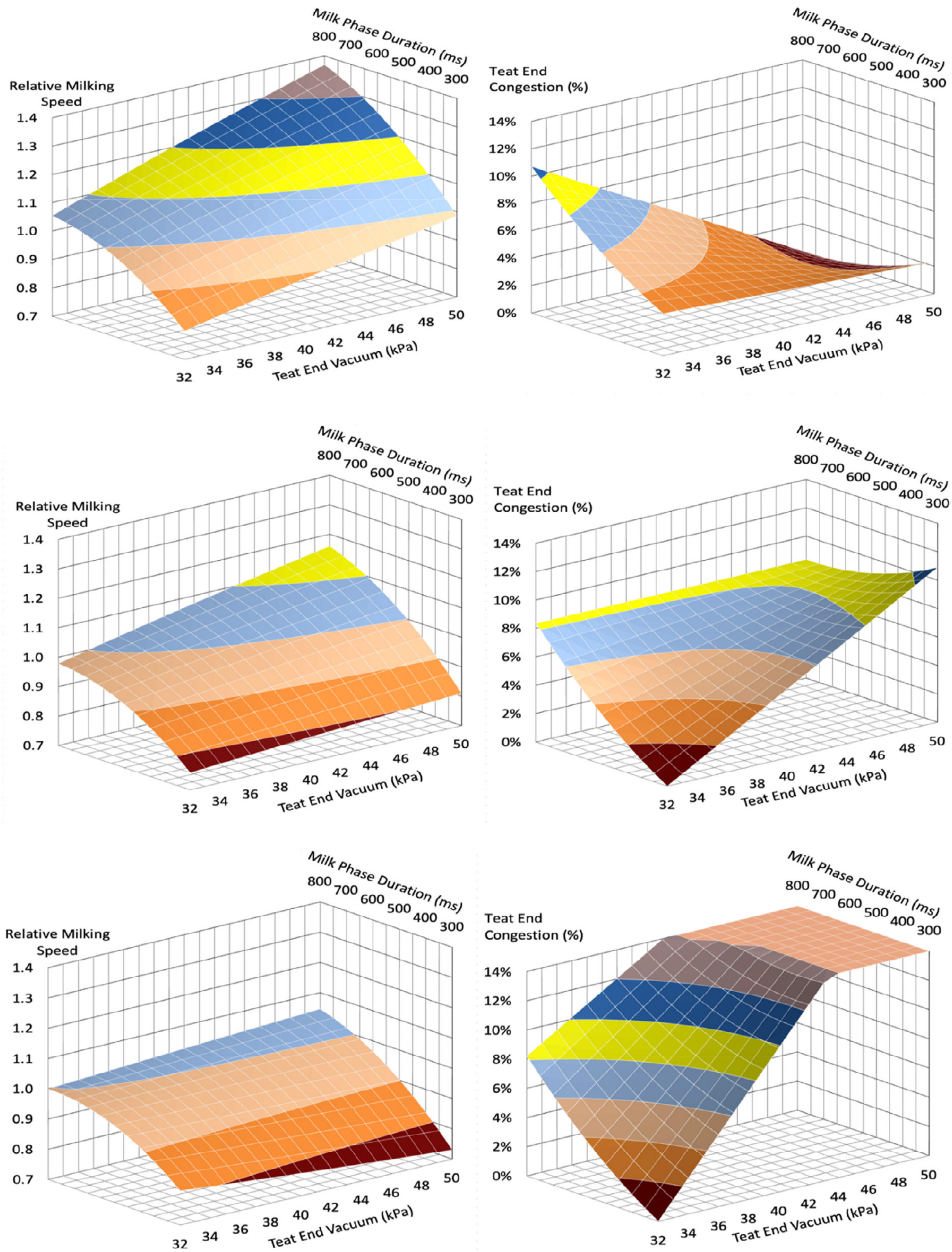

Figure 3. Response surfaces for liners with: high overpressure (OP; 8 kPa), producing about 5% of very rough teat-ends (top pair); medium OP (10 kPa), producing <2% of very rough teat-ends (middle pair); and low OP (2 kPa), producing <1% of very rough teat ends (bottom pair). The X-axes indicate teat-end vacuum, Y-axes indicate milk phase duration (rest phase duration was fixed at 200 ms). Left hand column is relative milking speed with 1.0 being the average milk flow (AMF) for each quarter. Middle column is teat-end congestion as indicated by the reduction of the teat canal cross sectional area from its maximum value for each quarter. Adapted from (Penry et al., 2018).

Automation, Labor, and Milking Individualization

As access to skilled labor declines in many dairy-producing regions, automation becomes a key driver of change. The early narrative around AMS focused on voluntary cow traffic, but the success of these systems is also due to features such as quarter-level milking, cow-specific machine settings, and, importantly, the lack of need for a human operator to be present during milking.

As in all production systems, increased precision is vital for improving productivity. Individual cows, and even individual quarters, differ significantly in their physiology and performance. Milking systems capable of automatically or semiautomatically adjusting to these individual differences offer the potential to optimize efficiency and animal comfort. One of the earliest steps toward individualization was the use of ACR. More recently, dynamic vacuum and pulsation settings have been developed to better balance the "evacuating forces" from the machine with the "ejecting forces" from the cow. By aligning the flow through the teat canal with the flow from alveolar tissue to the udder cistern, it is possible to achieve high milk flow rates without overmilking, at the udder level or even at the quarter level.

Milk Quality, Detection of Abnormal Milk, and Contaminants

Another critical development area is the reliable detection and rejection of abnormal milk. With advances in inline sensors, future systems will more effectively identify abnormal milk in real-time and automate its rejection. Increased precision in risk prediction will allow sensors to be used more efficiently and cost-effectively. In parallel, awareness is growing around contaminants in milk (including chlorates, iodine, and phthalates), as well as naturally occurring bioactive components. There is a growing expectation that milk quality assessments will go beyond fat and protein content. The true nutritional and functional value of milk is not fully reflected in current payment models, which may evolve in response to consumer and regulatory pressure.

Precision and the Role of Artificial Intelligence in Milking Dynamics

Future milking systems will increasingly incorporate individualized milking capabilities. Some will be powered by artificial intelligence, while others will rely on real-time observations within larger-scale, conventional systems. The line between AMS and conventional systems will become less distinct as all milking platforms integrate increasing levels of automation.

Examples include systems that adapt to differences in quarter-level yield when assessing completeness of milking. A higher degree of intelligence is expected in how milk extraction is controlled, both in terms of timing and yield, and how this interacts with metabolic disorders, milk synthesis, and optimal utilization of milking equipment.

What distinguishes a skilled milking technician today includes timing of stimulation, cluster attachment, and removal. Future systems will replicate and enhance these abilities, automatically stimulating, adjusting vacuum and pulsation, and individualizing milk removal for every cow, at every stage of lactation, and at every milking interval.

An emerging feature of milking systems is their ability not only to display and store data from individual milkings but also to process these data in real-time. By incorporating historical records, these systems can evaluate ongoing processes and feed the results back into the milking software to dynamically adjust single or multiple milking parameters. Such optimization may occur not just at the cow level but at the quarter level and may vary throughout different stages of a single milking.

One example is how machine intelligence can tune milking settings in real-time, particularly before milk ejection, to avoid harmful teat-end vacuum levels during bimodal milk flow. This can be achieved by predicting the timing of milk ejection based on expected udder fill, and adapting vacuum and pulsation settings to remain nondetrimental during periods of low milk flow.

System Architecture and the Business Value of Precision Milking

Although the focus of precision milking often centers on the cow or quarter, the efficiency and value of these developments are also shaped by the system in which milking occurs. Optimization of the milk extraction process typically centers on aspects of gentleness, performance, or both in synergy. Many recent developments have been driven by differences between cows, between udder quarters, or even dynamic changes occurring within a single milking of a single quarter. These innovations aim to accommodate such variability rather than applying a one-size-fits-all approach. As described previously, increased precision often leads to both improved performance and enhanced gentleness.

However, different milking systems have distinct operating characteristics that influence the business value of these developments. Every second of a cow's occupancy of an AMS stall has value, so time savings directly translate into system efficiency. In contrast, in a rotary or herringbone parlor, reducing milking time for the fastest cow may have little effect on overall throughput. In such systems, the benefit of increased precision may be limited by the broader system dynamics.

Batch milking with robots provides a good example of how to maximize efficiency in an automatic but nonvoluntary system. In these systems, every second of milking time still counts, and precision technologies can be applied to optimize each milking event even outside of a free-cow-traffic context.

CONCLUSIONS

The evolution of milk harvesting systems reflects a complex interplay between animal biology, technological innovation, and practical management. Although the physiological foundations of milk synthesis, ejection, and removal remain consistent, our ability to harness these processes efficiently has advanced dramatically. From the early mechanization of milking through the adoption of pulsation and vacuum systems, to the current era of AMS and precision control, the journey of milking technology has been both iterative and transformative. Efficiency in milk removal depends on a fine balance among speed, completeness, and gentleness. Key factors such as vacuum level, pulsation dynamics, liner design, and teatcup removal must be carefully calibrated to protect udder health and optimize milking outcomes. Research has deepened our understanding of how these machine-level variables interact with cow-level physiology, at both udder and quarter scales, enabling more individualized and responsive milking strategies. Looking ahead, the future of milk harvesting lies in systems that are more intelligent, adaptive, and biologically aware. Milking technologies will increasingly integrate data, sensors, and artificial intelligence to customize milking to the individual needs of each cow and each milking event. These advances promise not only improved efficiency and animal welfare but also better detection of milk abnormalities and more nuanced assessment of milk quality. Ultimately the goal of all milking systems, both present and future, remains the same: to milk cows as quickly, comfortably, and efficiently as possible, to a user-defined end point. With continued progress in engineering, data science, and animal biology, we are better positioned than ever to fulfill that goal in ways that are sustainable, scalable, and aligned with the evolving demands of both producers and the consuming public.

NOTES

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Nonstandard abbreviations used: ACR = automatic cluster removers; AMF = average milk flow; AMS = automatic milking systems; CCC = cow–calf contact; ISO = International Organization for Standardization; N = no teat-end rings; NIR = new intramammary infection rate; OP = overpressure; PFR = peak flow rate; PMF = peak milk flow; R = slightly roughened teat-end rings; S = smooth teat-end rings; TEHK = teat-end hyperkeratosis; VR = very rough teat-end rings.

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