Invited review: The impact of automatic milking systems on dairy cow management, behavior, health, and welfare

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ABSTRACT

Over the last 100 yr, the dairy industry has incorporated technology to maximize yield and profit. Pressure to maximize efficiency and lower inputs has resulted in novel approaches to managing and milking dairy herds, including implementation of automatic milking systems (AMS) to reduce labor associated with milking. Although AMS have been used for almost 20 yr in Europe, they have only recently become more popular in North America. Automatic milking systems have the potential to increase milk production by up to 12%, decrease labor by as much as 18%, and simultaneously improve dairy cow welfare by allowing cows to choose when to be milked. However, producers using AMS may not fully realize these anticipated benefits for a variety of reasons. For example, producers may not see a reduction in labor because some cows do not milk voluntarily or because they have not fully or efficiently incorporated the AMS into their management routines. Following the introduction of AMS on the market in the 1990s, research has been conducted examining AMS systems versus conventional parlors focusing primarily on cow health, milk yield, and milk quality, as well as on some of the economic and social factors related to AMS adoption. Additionally, because AMS rely on cows milking themselves voluntarily, research has also been conducted on the behavior of cows in AMS facilities, with particular attention paid to cow traffic around AMS, cow use of AMS, and cows' motivation to enter the milking stall. However, the sometimes contradictory findings resulting from different studies on the same aspect of AMS suggest that differences in management and farm-level variables may be more important to AMS efficiency and milk production than features of the milking system itself. Furthermore, some of the recommendations that have been made regarding AMS facility design and management should be sci-

entifically tested to demonstrate their validity, as not all may work as intended. As updated AMS designs, such as the automatic rotary milking parlor, continue to be introduced to the dairy industry, research must continue to be conducted on AMS to understand the causes and consequences of differences between milking systems as well as the impacts of the different facilities and management systems that surround them on dairy cow behavior, health, and welfare.

Key words: automatic milking system, robotic milking machine, behavior, health

INTRODUCTION

The US dairy industry has changed substantially over the last 100 yr. At the turn of the twentieth century, as the general population shifted from small rural villages to larger cities, the need for mass-produced and distributed milk products arose. Since then, significant advances in genetics, milking machines, nutrition, and farm management have combined to create the dairy industry we know today. These improvements have led to a 6-fold increase in average production per cow, considerably greater total annual milk production, and a sharp decrease in total cow numbers from 1900 to the present. For example, in the United States, the annual milk production per cow has tripled from 2,404 kg in 1953 to 9,049 kg in 2007, and dairy cow numbers, which peaked in 1944 at about 25 million, decreased to about 9 million cows by 2011 (USDA, 2008, 2011).

Much of the significant advancement in the twentieth century dairy industry has focused on maximizing milk production. Automatic milking systems (AMS) and automatic milking rotary (AMR) parlors represent the most recent technological efforts, offering the potential for frequent milking events without depending on human labor (de Koning et al., 2002). The first AMS were installed in the Netherlands in 1992, and by 2009, an estimated 8,000 farms worldwide had adopted AMS (Svennersten-Sjaunja and Pettersson, 2008; de Koning, 2010). The majority of AMS are located in northern Europe (90%) and Canada (9%), with only about 1% located in the United States (de Koning, 2010). Some of the reasons for slow adoption of AMS in the United

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States may include producer uncertainty about adopting the new technology and the lack of readily available service providers to assist with mechanical problems. In addition, the United States has a higher proportion of large farms than do countries that have more rapidly adopted AMS technology. Smaller farms adopting AMS may benefit more economically compared with larger farms (Armstrong and Daugherty, 1997; Rotz et al., 2003) and, thus, an AMS may be a less appealing option for many large dairy farmers. Last, US farmers may have more opportunity to find and hire cheap labor relative to other countries, potentially decreasing some of the appeal of an AMS. However, as research on AMS continues to address areas of customer and consumer concern, more widespread adoption in the United States is plausible. Additionally, introduction of the first AMR parlor, which was unveiled by DeLaval International AB (Tumba, Sweden) in 2010, means that now a robot is capable of serving larger group sizes. Each AMR, with a 24-stall platform, 5 robot arms, and a maximum capacity of 90 cows per hour, is designed to accommodate groups of 300 to 800 cows.

To date, scientific research has examined various aspects of AMS technology and its effect on milk quality, herd health, welfare, behavior, and management. Multiple differences exist between AMS and conventional parlors, making targeted research on new milking systems necessary. The fully automatic milking process of the AMS, which milks the udder on a quarter basis, and the automatic teat-cleaning and milking cup-attachment process have the potential to affect milk variables and udder health. Cows must be motivated to voluntarily approach and enter AMS milking stalls, as they are no longer brought to the milking parlor 2 or 3 times daily by human handlers. Additionally, most AMS are single-stall units, requiring cows to milk independently from herdmates. Providing adequate motivation for independent and efficient approach to, entry to, and exit from the milking stalls may be dependent on understanding cow behavior and, in turn, may affect cow welfare. Simultaneously, different management techniques need to be incorporated along with the AMS, as the daily routine is no longer driven by the herd's milking schedule and a large influx of automatically collected data becomes available.

Since the first AMS was installed in 1992, much research has been completed investigating these areas. However, as third and fourth generations of AMS become available and barn layouts and management routines have been optimized for AMS production, some of the older research may become obsolete. As manufacturers update AMS based on customer and industry feedback, research should examine and report on the resulting changes. A compilation of research

over the past 2 decades provides a way to reflect on the history of AMS, and serves as a method to identify areas needing additional research for the benefit of the dairy industry as a whole, and particularly for producers interested in acquiring an AMS.

HERD MANAGEMENT

Advantages of AMS Management

The most enticing initial aspect of an AMS to a farm manager may be relief from the daily milking routine (Jensen, 2004). However, an AMS has the potential to be more than a substitute of equipment for labor. Automatic sensors, particularly those that monitor udder health, milk production, reproductive status, feed intake, and BW changes provide detailed information about each cow, which was not easily obtained with previous management and milking systems (Spahr and Maltz, 1997). As a result, the health and production of individual animals can be monitored in greater detail. For example, an AMS allows the farmer to assess many aspects of cow health, including SCC (although this feature is not yet approved for use in the United States), color, and conductivity at the level of the udder quarter, which is currently beyond the ability of traditional milking systems. A farm manager who takes advantage of these features might be able to detect small changes within the individual cow to more quickly predict illness, as well as be able to watch for trends in overall herd production, potentially allowing for early detection of dietary or disease issues within the herd.

One of the main advantages of an AMS lies in the ability to control milking frequency on an individual cow basis to adjust for production level or at specific stages of lactation without incurring additional labor costs, assuming cows milk voluntarily at the desired frequency (Hogeveen et al., 2001; Svennersten-Sjaunja and Pettersson, 2008). Irrespective of parity, cows milked more frequently throughout lactation typically produce greater quantities of milk compared with cows milked twice daily (see Svennersten-Sjaunja and Pettersson, 2008 for a review relative to AMS). In experimental studies conducted in parlor milking systems, early lactation cows that were milked more frequently experienced increased milk (Hale et al., 2003; Dahl et al., 2004; Soberon et al., 2011). Further, even in the week before dry off, cows milked twice daily compared with once daily produced more milk (Tucker et al., 2009). However, lower milk yields at dry off can be beneficial, considerably decreasing the risk of IMI during the early dry period and at calving (Dingwell et al., 2004; Rajala-Schultz et al., 2005). Thus, the ability to adjust milking frequency to meet different goals at

different stages of lactation in AMS could benefit both production and cow health.

Several researchers have reported an increase in milking production of 2 to 12% in cows milking 2+ times per day in AMS compared with cows milking twice per day in conventional parlors (de Koning et al., 2002; Wagner-Storch and Palmer, 2003; Wade et al., 2004). For example, milk yield was found to be 9% higher in cows milked 3.2 ± 0.1 compared with 2.1 ± 0.1 (means $\pm$ SD) times per day in AMS (Melin et al., 2005a). However, other researchers have reported no increase in milk production related to increasing frequency of milking by AMS (Abeni et al., 2005a, 2008; Gygax et al., 2007). In particular, primiparous cows may not respond to increasing milking frequency in an AMS with increased milk yield (Abeni et al., 2005a, 2008; Speroni et al., 2006). Additionally, diet may affect the potential of increased milking frequency to result in increased yield, as cows in 100% grazing systems may not produce more milk when milked more frequently (Jago et al., 2007). High-yielding cows in AMS couple higher milking frequency with higher yield per milking, indicating that voluntary milking behavior and milk yield potential are both important factors to consider (Løvendahl and Chagunda, 2011).

Most AMS deliver a predetermined amount of palatable feed to cows during a successful milking event. Feeding concentrates in the AMS has multiple benefits. It provides an opportunity for the farmer to supplement an individual cow to support her stage of lactation, anticipated milk yield, or body condition. Additionally, the use of a highly palatable feed could be a strong motivator (Morita et al., 1996), creating a positive association for cows visiting the AMS (Madsen et al., 2010). Anecdotally, most AMS distributors indicate that feeding concentrates in the AMS provides cows with strong motivation for visiting the milking unit, and there is supporting research for this argument. Prescott and colleagues (1998) noted an increase in motivation for cows to visit the milking unit when concentrates were present. Furthermore, the authors concluded that the cow's motivation to be milked was weak compared with the motivation to eat, based on results from a choice test between milking and feeding (Prescott et al., 1998). Bach and colleagues (2007b) and Jago and colleagues (2007) found no significance difference between the amount of concentrate offered, the frequency of voluntary milking, and the need to fetch cows to the AMS. However, Madsen and colleagues (2010) noted that the composition of the concentrate offered in the AMS influenced the number of visits achieved. These results suggest that relying on cows' motivation to milk alone may not be sufficient and offering palatable feed

in the AMS or access to fresh pasture is necessary to encourage cows to enter the milking unit.

Cows' milking routines in AMS can be altered substantially relative to routines followed in conventional parlors and, in turn, this may make it beneficial for producers using AMS to reorganize traditional management and animal care activities and to manage at the level of the individual cow, not just at the group or herd level (Devir et al., 1997; de Koning and Rodenburg, 2004; Melin et al., 2005b; Svennersten-Sjaunja and Pettersson, 2008). If adjustments to the management routine are undertaken when automatic milking is implemented, these will simultaneously create new challenges and opportunities for both cows and producers as traditional roles change.

Disadvantages of AMS Management

Although the improvement in milking technology via the use of multiple sensors and data analysis programs in AMS can be beneficial to the manager and cow alike, certain disadvantages are also present. Dependency on sensors to detect estrus, abnormal milk, mastitis, and other health parameters can take detection out of the hands of the farm manager and shift it to a machine (Spahr and Maltz, 1997). With the automation of these measurements comes an influx of an enormous amount of data, which could be misinterpreted, used inappropriately, or even worse, ignored. As the focus shifts from traditional management methods and skills to a system reliant on new technology, the opportunity for, and impact of, computer and machine malfunctions increase. Traditional farm tasks and skills likely will change and, thus, some may eventually be lost.

The computerized management system of the AMS can control the maximum milking frequency for a cow and the maximum amount of feed to be dispensed to her at each milking. However, if the cow does not participate voluntarily in the milking and feeding routine, labor is required to complete these processes. Therefore, the cow's ability and motivation to individually access the milking stall become important to the overall success of the system (Hogeveen et al., 2001). The success of various strategies for encouraging voluntary milking visits will be reviewed in future sections of this document.

Each single-stall AMS is estimated to cost \$150,000 to \$200,000 and can serve approximately 60 cows, depending on the number of milking events the farmer strives to attain for each cow per day. In comparison, a new conventional parlor is estimated to cost between \$4,000 and \$15,000 per milking stall, depending upon the type of parlor and whether or not an exist-

ing shell (e.g., concrete and plumbing) can be reused. This means that a double-6 parlor might cost between \$48,000 and \$180,000. Thus, traditional parlors are not always inexpensive ventures. However, the conventional parlor price is singular, whereas farmers might need to purchase multiple AMS to accommodate their herd. Furthermore, it may be more challenging for farmers to gradually increase the size of their herds with AMS than with conventional milking parlors, as an AMS has fairly strict constraints on the number of cows it can service. When deciding between investing in an AMS or a conventional parlor, dairy producers must weigh the decreased labor needs of the AMS against the increased fixed costs and possibly faster depreciation when milking with an AMS (Bijl et al., 2007).

Individual cows may have behavioral or conformational aspects that make them unsuitable for integration into a robotic milking herd. Undesirable teat position and udder quarter size variation create difficulties for cluster attachment in AMS. In a survey of 15 North American dairy producers, all reported difficulties with teat variation and cluster attachment, resulting in 0 to 3 extra culls per year from herds with an average of 94 cows (Rodenburg, 2002). Miller and colleagues (1995) suggested that the greatest obstacle for cluster attachment by AMS was the distance between rear teats, where touching rear teats were seen as one teat by the sensor. Additionally, Rodenburg (2002) found a connection between very high rear udder floors and cluster attachment failure, suggesting it was difficult for the sensor to see the high rear teats in a horizontal plane. In the New Zealand Greenfield herd, 8% of potential new cows were rejected due to conformations that were anticipated to result in cleaning and milking difficulties (Woolford et al., 2004).

Following teat cup attachment failure, milk production by the quarter that failed to be milked was 26% lower during the subsequent milking once interval length was corrected for (Bach and Busto, 2005). The effect of milking failure on milk production by a quarter was more pronounced as DIM increased. Milk production by unaffected quarters also decreased if there was a long interval between the milking with a quarter failure and subsequent milkings. However, milk production recovered to prior levels within 7 milkings following a failure.

The success rate of AMS cluster attachment in commercial herds ranges from 85 to 98%, with higher success rates in more recent surveys and studies, suggesting technological improvement in this aspect of the milking process (Miller et al., 1995; Mottram et al., 1995; Gygas et al., 2007). However, in one study, a 7.6% failure rate of teat cups to attach to at least 1 quarter during milking was observed, even after all quarters

had been successfully located and cleaned (Bach and Busto, 2005). Thus, it may prove to be incumbent upon managers to assess udder and teat conformation before admitting a cow to the milking herd or to consider genetic selection for desirable teat placement, to avoid devoting labor to milking the anticipated 15% of the herd that will experience cluster attachment difficulties and failed milkings.

A final disadvantage to adopting AMS is that dairy managers need to be willing to commit time to training their herds as a whole to use the AMS, as well as individual animals as they enter the milking herd and encounter the AMS for the first time. Transitioning a herd from a conventional parlor to an AMS takes approximately 3 to 4 wk of intense labor to achieve a success rate of 80 to 90% cows using the system voluntarily (Rodenburg, 2002; Jacobs and Siegford, 2012). However, the speed of adaptation may vary widely among individuals in the herd, potentially influenced by coping response, age, and experience (Weiss et al., 2004; Munksgaard et al., 2011). Pre-exposure to the AMS (i.e., exposure to typical noises and mechanical movements within the milking stall) appears to improve the ease of entry into the AMS upon first milking (Jago and Kerrisk, 2011). Regardless of the level of pre-exposure, primiparous cows seem to adapt to the AMS more quickly than multiparous cows (Jago and Kerrisk, 2011).

COW BEHAVIOR

Cow Traffic

An AMS provides a cow with the potential to set her own milking schedule, assuming that she is able to act as an individual apart from her herd. It has been suggested that the number of daily milkings and feedings cows can obtain in an AMS, as well as the number of times cows must be fetched to an AMS, are influenced by the design of cow traffic systems within the barn (Ipema, 1997; Ketelaar-deLauwere et al., 1998). Cow traffic refers to the series of gates (or lack thereof) that force cows to follow a set pattern through the barn. Much debate has taken place regarding the type of cow traffic system that facilitates both high AMS visit frequency and provides adequate access to lying stalls and feed (Ketelaar-de Lauwere et al., 1998; Hermans et al., 2003; Bach et al., 2009). Forced or one-way cow traffic requires cows be milked before visiting the feed alley. Essentially, in these systems, a circuit is formed in which cows can move in only one direction to feed, lie down, and be milked. Guided cow traffic uses selection gates to assess whether cows are due for milking before they can access the feed area. If their designated milk-

ing interval has expired, cows in guided traffic systems are directed to the AMS to be milked before accessing the feeding area. Free cow traffic allows cows to freely move between feed alleys, lying stalls, and the AMS at any time they choose.

AMS Use. A few researchers have indicated that forced cow traffic encourages more visits to AMS compared with free cow traffic (Ketelaar-de Lauwere et al., 1998, 2000a; Bach et al., 2009). In one such study, the authors reported 953 visits to the AMS over 4 d with forced cow traffic compared with 703 AMS visits with free cow traffic (Stefanowska et al., 1999). However, the cows in the forced-traffic situation had more milking failure visits [1.2 per cow per day compared with 0.6 per cow per day (i.e., cows entered the AMS but were not milked because the minimum interval between milkings had not yet been reached)]. In effect, the average successful milking frequency was not significantly different between the 2 traffic systems, which agrees with the findings of other studies (Hermans et al., 2003; Munksgaard et al., 2011). Similarly, in a direct comparison of AMS with free or guided traffic, no difference was found in successful milking frequency, but 97.5% of all AMS visits in the free-traffic system were successful compared with 89.7% in the guided traffic system (Gygax et al., 2007). The motivation behind unsuccessful visits to AMS should be examined to decrease the amount of AMS time that is wasted in this manner.

A large waiting area located in front of the AMS has been deemed important by several authors, as it can decrease social competition for the AMS, particularly for low-ranking cows (Uetake et al., 1997; Hermans et al., 2003; Melin et al., 2006). Some researchers have also indicated the need for selection gates throughout the barn to facilitate efficient use of the AMS for cows of all ranks and decrease the need for fetching (Ketelaar-de Lauwere et al., 1998; Stefanowska et al., 1999; Bach et al., 2009). Thus, a barn being built for or adapting to an AMS will benefit from features that encourage efficient cow traffic and promote voluntary milking as well as normal lying and feeding behavior (Armstrong and Daugherty, 1997).

Feeding and Lying Behavior. Feeding behavior and feed intake are also important aspects to consider when deciding between traffic systems. With guided and forced cow traffic, cows must pass through selection gates before accessing the feed alley, which can potentially affect daily feed intake and milk production. A few authors have reported increased concentrate and total DMI in facilities using forced or guided cow traffic compared with free cow traffic (Hermans et al., 2003; Melin et al., 2007), whereas others have found that DMI did not differ between the traffic situations (Ketelaar-

de Lauwere et al., 1998) or that the number of visits to the feed area decreased in forced traffic (Munksgaard et al., 2011). Contradictory reports have been published on the number of daily meals between traffic systems. Bach and colleagues (2009) determined the number of daily meals to be fewer with longer duration with forced cow traffic, contrasting with the results of others who reported no differences in the number of meals or visits to the feed alley (Melin et al., 2007; Lexer et al., 2009). If cow traffic does negatively affect feeding behavior, it is likely that primiparous cows will be most affected, which might compound difficulties in meeting their nutritional requirements early in lactation (Abeni et al., 2005a, 2008).

The discrepancies between feeding studies could be attributed to differences in conditions under which the studies were conducted, such as differences in feed palatability, feed management, water access, and herd health, as well as to differences in how meals, feeding bouts, and feeding visits were measured (Melin et al., 2005b). Alternatively, Melin and colleagues (2005b) suggest that individual cows develop a unique, consistent feeding and drinking pattern. In one study, the majority of the random variation in feeding patterns of cows was due to individual differences (84–98%; Melin et al., 2005b), which could also help explain differences in feeding behavior reported in the previously mentioned studies.

Regardless of the type of traffic system, diurnal patterns of feeding and lying behavior persist in AMS, with fewer cows feeding and more cows lying down overnight (Wagner-Storch and Palmer, 2003; DeVries et al., 2011; Jacobs, 2011; Munksgaard et al., 2011). Wagner-Storch and Palmer (2003) reported lower, more consistent percentages of cows at the feed bunk in an AMS system with one-way traffic relative to feed bunk attendance by cows being milked in a parlor. These findings suggest that AMS may require less feed bunk space per cow, as groups appear less likely to feed simultaneously compared with cows in a parlor situation.

Even though humans do not manage cows' milking routines in AMS, cow behavior in AMS is still affected by human actions. For example, both milking and feeding behavior increased in AMS after overdue cows were fetched to be milked at 0700 h, as evidenced by higher percentages of cows in the AMS and waiting area between 0800 to 1300 h and 0800 to 1100 h, respectively (Wagner-Storch and Palmer, 2003). Fetching also stimulated milking over a 2-h period in a study by Belle and colleagues (2012). Delivery of fresh feed or feed push up near the time of milking also appeared to result in more synchronized feeding behavior and in cows lying down more quickly following milking (DeVries et al., 2011; Munksgaard et al., 2011). Thus, even though cows in

AMS may not feed with the degree of synchrony seen in parlor systems, the fact that delivery of feed and fetching cows to milk can affect cows' behavior should be investigated further to optimize feeding behavior in AMS.

Cows have limited access to stalls in guided- and forced-traffic systems; thus, they might be expected to spend less time lying each day. However, several studies have found no significant difference in lying times among forced, guided, and free cow traffic systems (Hermans et al., 2003; Lexer et al., 2009; Munksgaard et al., 2011), whereas others have observed total time standing in a forced cow traffic situation to be significantly greater compared with free cow traffic (Ketelaar-de Lauwere and Ipema, 2000).

Behavior Near AMS

The success of the milking visit can have a significant effect on cows' behavior near the AMS, potentially affecting its use by other cows and decreasing milking efficiency (Stefanowska et al., 1999; Jacobs et al., 2012). For example, the time taken to exit the AMS was found to be shorter after successful milking visits than after unsuccessful visits, and cows were more likely to immediately re-enter the AMS after an unsuccessful visit (Stefanowska et al., 1999; Ketelaar-de Lauwere et al., 2000a; Jacobs et al., 2012). Further, cows exiting the AMS hesitated longer while exiting when other cows were near the AMS exit gate (192.93 ± 1.11 s) or in the waiting area (101.04 ± 1.07 s) compared with when no cows were present (88.11 ± 1.07 s; Jacobs et al., 2012). Cows in late lactation had a greater probability of hesitating in the exit alley for long periods (0.55 ± 0.09) compared with cows in early lactation (0.15 ± 0.07), regardless of whether other cows were in the holding area (Jacobs et al., 2012).

In some cases, cows may have difficulty leaving the AMS after milking because other cows are standing at the AMS exit gates, effectively blocking their exit from the system (Stefanowska et al., 1999). In one study, primiparous cows were more likely to block cows from exiting (0.60 ± 0.13) compared with multiparous cows (0.29 ± 0.09). Occasionally, a cow's blocking of the exit can make the AMS unavailable for subsequent milkings due to a back-up of cows through the exit gates into the milking stall (Jacobs et al., 2012). In this study, the AMS were empty 10 to 18% of the day; therefore, it was possible that back-up events would decrease the amount of time the AMS was empty and not affect successful milking. However, although duration of back-up events and AMS empty events had a negative relationship in group 1 ($r = -0.74$, $P < 0.01$), no relationship between back-up events and AMS empty events was

observed in group 2 ($r = -0.14$, $P = 0.61$). The differences in relationships between back-up events and AMS empty time between the groups studied suggests that behavior of individual cows or social dynamics within a group may play a substantial role in efficient use of AMS (Jacobs et al., 2012).

Enough evidence exists to suggest that a delicate balance must be achieved, with cows motivated to voluntarily approach the AMS to decrease farm labor while avoiding unproductive visits to help promote an efficient system and maximize use of the AMS. A need exists for more research in this area, including modeling the effect of individual and group behavior on blocking, back-ups, exit speed, and unsuccessful visits on the availability of the AMS.

Voluntary Milking Behavior

Timing and Frequency. Diurnal patterns are often reported for milking behavior in AMS, with less milking occurring between 2200 and 0700 h (Wagner-Storch and Palmer, 2003; Abeni et al., 2005a), although such lengthy or dramatic changes in AMS occupancy are not always observed (Hogeveen et al., 2001; Bach et al., 2007b; DeVries et al., 2011; Munksgaard et al., 2011). In situations with forced traffic or waiting areas, concomitant surges in the number of cows in the waiting area may also be observed at times of high AMS use (Wagner-Storch and Palmer, 2003).

Although in theory, milking frequency can be increased in AMS by setting the system to allow cows to milk more frequently, it may not be realistic to expect a herd average of more than 3 milkings per day (Dzidic et al., 2004b; Melin et al., 2005a). For example, when Melin and colleagues (2005a) set milking intervals at 4 h (i.e., 6 times per day) versus 8 h (i.e., 3 times per day), they found that actual milking frequency was 3.2 ± 0.1 compared with 2.1 ± 0.1 (means $\pm$ SD) times per day in the 2 treatments, respectively. Reported milking frequencies for experimental and commercial herds range between 1.9 to 3.2 milkings per day (e.g., Rousing et al., 2006; Bach et al., 2007b; Borderas et al., 2008; André et al., 2010). Lower milking frequencies, in the 1.4 to 1.9 milkings per day range, are often seen in systems with 100% grazing or that offer only small amounts of concentrate in the AMS (e.g., Jago et al., 2007; Davis et al., 2008). However, voluntary milking rates of greater than 3 times per day have been documented in studies using primiparous cows (Abeni et al., 2005a; Munksgaard et al., 2011).

Milking Interval. The high degree of individual variation in milking frequencies leads to wide variation in milking intervals (e.g., 4–36 h), with some cows milking as soon as the minimum interval allowed has elapsed,

whereas others are milked when the producer fetches them in response to AMS alerts (Friggens and Rasmussen, 2001; Dzidic et al., 2004b; Melin et al., 2005a). In a study by Gygas and colleagues (2007), 67% of milking intervals were 6 to 12 h, with 11% of intervals <6 h and 21.5% of intervals lasting >12 h. Similarly, other studies have reported that although the most frequent milking interval was 7 to 8 h, very short (<4 h) and very long intervals (>12 h) were regularly observed (Hogeveen et al., 2001; Abeni et al., 2005a). Long milking intervals of 12 and 16 h preceded 17.6 and 4.2% of all successful milkings, respectively, whereas short intervals of 4 and 6 h preceded 0.5 and 9.7% of all successful milkings, respectively (Hogeveen et al., 2001). When a large degree of irregularity in milking interval length was observed, daily milk yield decreased as a result of a decrease in apparent milk synthesis rate (Bach and Busto, 2005). Yield in multiparous cows decreased linearly with increasing variation in milking interval, whereas in primiparous cows, yield only decreased if the weekly coefficient of variation for milk yield interval was >27% (Bach and Busto, 2005).

Some of the variation in milking interval is likely a natural result of stage of lactation. Dzidic and colleagues (2004b) found that milking interval increased throughout lactation and was (means $\pm$ SEM) 8.2 ± 0.1 h in early, 9.6 ± 0.1 h in mid, and 11.1 ± 0.2 h in late lactation, respectively. Further, different interval lengths may have a different effect on milk production between individual cows (André et al., 2010). In practice, what this means is that rather than using a general formula based on DIM and expected milk yield to set milking intervals, information from the AMS could be used to set optimal interval lengths on an individual cow basis to optimize AMS use (André et al., 2010). Further, in the future, it may be shown that some variation in interval length may be explained by cow-related factors, including higher general activity of primiparous cows, social rank, or differences in motivation to eat the concentrate provided in the AMS.

Fetching

A high percentage of voluntary milking events is necessary to successfully decrease labor on any farm milking with an AMS. Fetching is more frequent during the first 14 d of lactation (i.e., 56–100% of cows must be fetched at least once) when the cows are learning or remembering how to use the AMS (Rousing et al., 2006; Jacobs and Siegford, 2012). Following the training period, 6 to 42% of cows must be fetched at least once per day to be milked by the AMS (Rodenburg, 2002; Rousing et al., 2006; Jacobs and Siegford, 2012). Cows with udder conformation making it difficult for

teat cups to attach were reported to be fetched twice as often as herd mates without conformation problems (Jacobs and Siegford, 2012).

Although most farmers indicate that minimal effort is required for fetching, the need to fetch cows remains one of the main concerns producers have about AMS, and may be the single largest factor preventing producers from realizing anticipated labor savings (Bach et al., 2007b). In a recent Canadian survey, producers reported fetching 4 to 25% of their cows, although variation between herds was large (Rodenburg and House, 2007). The 5 best herds fetched 2.5% cows, on average, whereas the 5 worst fetched an average of 41.6% of their cows once or twice daily. This indicates that creating conditions that facilitate a voluntary approach to the AMS is still a dilemma, although individual management styles and facility designs may dictate the degree to which fetching is a problem.

In an effort to characterize whether cows that needed to be fetched found being milked by AMS aversive, Rousing and colleagues (2006) studied whether differences existed between fetched and non-fetched cows with regard to reluctance to enter the AMS, stepping or kicking during milking, or avoidance of human handlers. Whereas 37% of cows showed reluctance to enter the AMS, the authors found no difference in reluctance between cows that were fetched and those that milked voluntarily. Also, no significant interactions were observed between stepping and kicking during milking and fetching for milking. However, cows that had to be fetched for milking showed a greater avoidance distance when approached by a familiar person (Rousing et al., 2006). However, at this point, it is unclear whether fetching resulted in increased avoidance distance or whether the cows that needed to be fetched were more fearful or timid initially, which could have resulted in a greater need to fetch them.

COW WELFARE

The welfare of dairy cows on any farm is affected by multiple factors. Social interactions with other cows, human-animal interactions, management systems, feeding practices and nutrient supply, barn design, climate, and other environmental conditions can affect cow welfare in both negative and positive ways (Wiktorsson and Sørensen, 2004). Compared with cows milked in conventional parlors, cows in AMS have more freedom to control their daily activities and rhythms and have more opportunities to interact with their environment. However, most AMS are single-stall units, resulting in an isolated milking experience that drastically differs from most conventional parlor systems. Social isolation in unfamiliar surroundings has been suggested to

increase stress responses in dairy cattle (Rushen et al., 1999, 2001). As a result, different animal welfare implications may be associated with the AMS.

Behavioral and Physiological Stress Responses to Different Milking Systems

Several researchers have compared the welfare of cows in AMS and conventional parlor systems. Hopster and colleagues (2002) compared differences in behavioral and physiological stress responses of primiparous cows during milking in an AMS and a tandem milking parlor. The authors reported that cows milked in an AMS had a lower heart rate and lower maximum plasma adrenaline and noradrenaline concentrations, suggesting decreased stress during milking. Wenzel and colleagues (2003) determined that cows' heart rates rose significantly in the minutes before entering the AMS milking stall; however, this increase resulted in heart rates of AMS cows that were similar to those of the parlor-milked cows upon start of milking. Heart rate decreased over the course of milking in both AMS and parlor systems, reaching similar rates in both groups by the end of milking (Wenzel et al., 2003).

Feed is offered during milking in AMS, and the acceleration in heart rate observed in some studies before or during milking in AMS may be due to anticipation of feed or feeding behavior. Although increased heart rates associated with a positive experience have not yet been demonstrated in cattle, studies using rats and pigs have found similar increases in heart rate associated with both positive and negative stimuli (Seward et al., 1969; Paul et al., 2005).

When heart rate was measured during milking, Hagen and colleagues (2005) found no difference in heart rate variables between AMS and parlor milking systems. However, when they examined the heart rates of cows lying down in both systems, they found substantial differences in several parameters, suggesting that the partially forced traffic in the AMS they examined may have caused cows to experience chronic stress (Hagen et al., 2005). Gygax and colleagues (2008) also found differences in heart rate variables between cows milked with AMS and parlors that suggested increased stress associated with one type of AMS. Higher levels of cortisol in milk, which reflects the concentration of plasma cortisol during the period of milk synthesis before milking, as well as higher basal levels of plasma cortisol have also been found between AMS-milked and parlor-milked cows (Wenzel et al., 2003; Hagen et al., 2004; Abeni et al., 2005a). It should be noted that in the studies mentioned above with higher cortisol levels or heart rate variables indicative of chronic stress, some type of forced- or guided-traffic system regulating ac-

cess to the AMS and to feeding or resting areas, or both, was in place. In studies that directly compared AMS with either free or guided/forced traffic with parlor systems, no differences were found in milk cortisol between the systems, although heart rate was elevated in both AMS types (Gygax et al., 2006; Lexer et al., 2009).

In a study examining the response of cows transitioning to an AMS from a parlor, cows showed elevated heart rates during their first training visit to the AMS (Weiss et al., 2004). However, during subsequent training visits and during first milking, the cows' heart rates were similar to those seen when they were milked in a conventional parlor. No difference was seen in levels of fecal corticosteroids between the parlor and AMS, even during transition (Weiss et al., 2004). These results are similar to the changes in stress-related behaviors observed by Jacobs and Siegford (2012), following the transition of cows from a parlor to AMS. Vocalization, defecation, and urination are indicators of acute stress or fear in cattle (de Passillé et al., 1995; Grandin, 1998). Urination, defecation, and vocalization were observed during milking by the AMS on the day of transition but quickly dropped to no occurrences on subsequent days (elimination: $d\ 0 = 3.1 \pm 0.09$, $d\ 1 = 0.6 \pm 0.07$, and 0 ± 0 instances thereafter; vocalization: $d\ 0 = 1.7 \pm 0.07$, $d\ 1 = 0.05 \pm 0.04$, and 0 ± 0 (means $\pm$ SEM) instances thereafter; Jacobs and Siegford, 2012).

Increased movement (stepping and kicking) by cattle is considered a sign of agitation (Grandin, 1993) and has been used frequently to assess cow comfort during milking. Hopster and colleagues (2002) noted no differences between AMS and a conventional parlor when comparing steps and kicks during the milking event, whereas Hagen and colleagues (2004) found less stepping and kicking in AMS. In particular, more stepping and kicking was observed during attachment in the parlor (Hopster et al., 2002; Hagen et al., 2004). This could be due to discomfort or to aversion to the human handler during cleaning and attachment in the parlor system. Several studies have found step-kick rates to be highest in AMS during the end of milking, when the teat cups detach one at a time as each quarter finishes milking (Hopster et al., 2002; Jacobs and Siegford, 2012). Conversely, Wenzel and colleagues (2003) determined that step-kick behavior occurred significantly more often in all phases of milking by AMS compared with the milking parlor.

When interpreting these results, it must be remembered that the duration of time and the process by which the teat cups are attached and removed between AMS and parlor systems is very different (e.g., removal being longer and sequential in the AMS with quarter milking, and almost instantaneously in the parlor with

all cups removed together), as is the degree of human handling. These differences make it challenging to compare step and kick rates between AMS and parlor systems. In addition, management or health differences in the herd, rather than differences in milking systems, could be the primary cause in these discrepancies. For example, Rousing and colleagues (2004) reported that the frequency of stepping and kicking behavior during milking varied from 6 to 61% between herds in conventional parlors.

Even when comparing types of AMS, differences can exist in cow response. In a direct comparison between a Lely Astronaut A3 AMS (Lely Holding S.à r.l., Maassluis, the Netherlands), a DeLaval VMS (DeLaval International AB), and a conventional milking parlor, the investigators reported that cows in the DeLaval system exhibited a higher rate of stepping during teat cleaning and milking, a greater tendency to kick, and higher heart rate during milking compared with the Lely AMS and the parlor (Gygax et al., 2008). However, the authors did note that teat cup attachment was less successful in the DeLaval system compared with the Lely AMS (94.3 vs. 98.4% of milkings). This could indicate that udder conformation and teat arrangement of cows on the farms with the DeLaval systems were less than ideal, management or health differences existed between the herds, or that imperfections existed in the design or mechanics of the DeLaval system. The most important difference between the Lely and DeLaval AMS is the service arm and how it moves to clean teats and attach cups, with the DeLaval service arm moving more frequently. Any of these possibilities could help to explain the cows' increased discomfort with this system. Unfortunately, no other studies have directly compared AMS types, indicating a need for further investigation in this area. If a difference in cow comfort does exist between the different types or generations of AMS, it could help explain some of the differing physiological and behavioral outcomes reported among studies.

Social Hierarchy

It has been demonstrated that low-ranking cows are forced by social competition to visit the AMS at times that are not preferred, particularly during the midnight hours (Hopster et al., 2002). This suggests that when a lower-ranked cow can milk depends on other cows' schedules. If this is the case, irregular milking intervals could be the result for low-ranking cows, which could impair milk production (Ouweltjes, 1998; Hogeveen et al., 2001) or have a negative effect on SCC (Mollenhorst et al., 2011). Therefore, any anticipated increase in milk production with an AMS may not be fully realized, particularly for low-status cows in the

herd. Halachmi (2009) reported an average wait time (means $\pm$ SE) in the AMS cow queue of 68.9 ± 6.5 min for low-ranking cows, compared with an average of 3.5 ± 0.11 min for high-ranking cows, suggesting that when other factors were held constant, social rank had some effect on the time budget of cows in an AMS. Lower-ranking cows may also be required to wait for access to the AMS more often than higher-ranking cows and may not be able to milk during times of peak AMS use (e.g., afternoon; Ketelaar-de Lauwere et al., 1996).

HERD HEALTH

Metabolic and Immune Status

Because cows have the ability to milk more frequently in AMS, it is important to investigate the effect this may have on cows' energy balance and immune function, particularly during early lactation. When examining the effect of milking frequency in AMS on BCS, no significant differences were found in the first 19 wk of lactation between cows milking 3.2 ± 0.1 compared with 2.1 ± 0.1 times per day [e.g., 2.8 ± 0.2 vs. 2.9 ± 0.2 (means $\pm$ SE) BCS during wk 11 to 16 of lactation; Melin et al., 2005a]. Several studies examining the metabolism of cows milked by AMS or parlors have found no differences in BCS, levels of energy-related metabolites, including triglycerides, glucose, BHBA and NEFA, or urea (Wenzel and Nitzschke, 2004; Abeni et al., 2005a, 2008). In one study, AMS cows had lower total plasma cholesterol than parlor-milked cows (3.252 ± 0.179 vs. 3.922 ± 0.184 mmol/L, means $\pm$ SEM, respectively) and a greater NEFA:total cholesterol ratio (0.185 ± 0.018 vs. 0.133 ± 0.018 , means $\pm$ SEM) throughout the first 14 wk of lactation; however, this ratio was affected by both greater NEFA values in the AMS compared with the parlor in the first week of lactation and lower total plasma cholesterol values in the AMS (Abeni et al., 2008). Immune function, as assessed by examining oxidative status through measurement of plasma reactive oxygen metabolites and thiol groups, also does not appear to be affected by milking system (Abeni et al., 2008).

Hillerton and colleagues (2004) investigated 15 farms from 3 different countries (Denmark, the Netherlands, and the United Kingdom) making the change from conventional milking to automatic milking. The authors determined that BCS varied more by country than it did as a result of the transition to an AMS. Dearing and colleagues (2004) made a similar conclusion; they found no significant difference in BCS during and after the transition to automatic milking. Both authors noted a large amount of variation in BCS between herds and between countries irrespective of the transition; there-

fore, BCS may more accurately reflect herd health and management, rather than the type of milking system.

Lameness

Galindo and Broom (2002) noted that a lame cow is less able to cope successfully with her environment, as pain might seriously affect walking and other movements. When combined with automatic milking, this observation becomes notably more important, as a cow with painful feet and legs might be less willing to approach the AMS voluntarily (Borderas et al., 2008). Bach and colleagues (2007a) reported decreased AMS visits and higher fetch rates for cows with high locomotion scores (scores of ≥ 3 on an increasing severity scale of 1 to 5) relative to cows with low locomotion scores. Similarly, in a study of 8 Danish herds being milked with AMS, cows classified as lame had a lower milking frequency than healthy cows (Klaas et al., 2003). Cows that visit the AMS less have also been found to have higher gait scores (mean $\pm$ SD: 2.5 ± 0.8 vs. 1.8 ± 0.4 , respectively) than cows that visit the AMS voluntarily more often (Borderas et al., 2008).

Therefore, it becomes particularly important to investigate locomotion and lameness associated with the AMS. When building or modifying a new facility to accommodate an AMS, necessary changes may result in increased lameness (e.g., new concrete flooring can be abrasive and have a negative effect on hoof health; McDaniel, 1983). A few researchers have reported no significant differences in the severity or quantity of lameness associated with the transition to an AMS, when holding other features of the barn and management constant (Hillerton et al., 2004; Vosika et al., 2004). It is probable that lameness is more closely associated with management and facility design rather than the type of milking system.

Some AMS use 4 load cells on the floor of the milking stall to detect shifts in a cow's BW. This feature allows the robotic arm to remain directly under the udder at all times. At present, the 4 load cells do not report the force of each limb separately. However, AMS software could be designed to allow for separate analysis of the force exerted on each load cell to automatically detect changes in weight distribution indicative of lameness as cows are being milked (Pastell et al., 2008). This could be a powerful management tool, allowing producers to detect lameness problems in early stages when intervention is most effective and least expensive.

Estrus and Estrus Detection

In general, milking with an AMS does not appear to affect most measures of reproductive success (Kruip et

al., 2000; Dearing et al., 2004). However, differences have been observed in conception rates and services 1 mo after AMS installation, and slight decreases in fertility (although not significant) have been seen up to 12 mo after installation (Kruip et al., 2002; Dearing et al., 2004). For the full consequence of any changes in fertility to be studied, longer trials are required, and as automated estrus detection mechanisms improve or producers devote more time to observing cow behavior once they have adapted to the new milking system, this situation may resolve. Thus, with short-term studies from only a few authors, further research is needed in this area.

Transponders allow for automatic identification of a cow when she enters the milking stall. In addition, some manufacturers offer transponders coupled with activity and rumination monitors. The activity monitors can measure and record the number of steps a cow takes each day. Increased activity is strongly correlated with low progesterone during estrus (Durkin, 2010); therefore, it may be used as a timing tool for AI. Durkin (2010) recorded estrus detection specificity using an Afikim/DeLaval activity monitor, reporting an 82% average detection rate over 6 trials with a range of 73 to 92%. The low detection rates likely resulted from a combination of lame cows that did not show activity during estrus and misinterpretation of the data. Automatic activity detection can allow for less intense visual monitoring of estrus; however, the farmer still needs to be able to access and interpret the data from the AMS.

Udder Health and Hygiene

Early studies suggested that milking by an AMS led to poorer teat and udder health compared with conventional milking systems (Ipema and Benders, 1992; van der Vorst and Hogeveen, 2000; Rasmussen et al., 2001). Ipema and Benders (1992) associated the decrease in udder health with deterioration in teat orifice condition. More recently, however, transitioning to an AMS has been reported to either cause no change to teat end condition or to result in significant improvement (Berglund et al., 2002; De Vlieghe et al., 2003; Neijenhuis et al., 2004; Zecconi et al., 2004). Earlier models of the AMS typically had longer machine-attachment times compared with more recent AMS, which may have been a cause of decreased udder health reported in early studies. Teat trauma can be amplified by over-milking (Hillerton et al., 2004); thus, theoretically, quarter milking by AMS should reduce the likelihood of over-milking, which could result from one slow quarter in a conventional system. A recent review of udder health in AMS identified that automatic detection of subclinical and clinical mastitis, as well as detection of dirty

udders and thorough teat cleaning, remain the highest risks for poor udder health in an AMS (Hovinen and Pyörälä, 2011).

Cleaning Success. The udder health of cows is partly dependent on proper milking hygiene (Bartlett et al., 1992), and contamination of the teat orifice can occur easily through bacteria on teat surfaces or on contact surfaces of milking equipment (Hovinen et al., 2005). Therefore, the cleanliness of the teat and equipment before milking is essential. In an AMS, the cleaning no longer depends on the decision-making abilities of the herdsman. There are presently 4 different devices for teat cleaning used by various AMS: 1) simultaneous cleaning of all teats by a horizontal rotating brush, 2) sequential cleaning by brushes or rollers, 3) simultaneous cleaning of all teats in the same teat cups as used for milking, and 4) sequential cleaning of individual teats by a separate cleaning device. Extra care may be needed to clean teats in AMS, as none of the 4 systems dries teats before the start of the milking process, thus eliminating another opportunity to remove bacteria from the teat orifice.

Evidence exists of an association between udder contamination with manure and the number of mastitis bacteria on teat ends (Bramley et al., 1981; Pankey, 1989). Therefore, teat cleaning becomes particularly important as a measure to prevent mastitis. Jago and colleagues (2006) observed 130 teat-cleaning periods in AMS and found that only 67% of the cleanings were technically successful (i.e., all 4 teats were completely brushed). Similarly, Hvaale and colleagues (2002) observed approximately 10 to 20% of the teat cleanings per cow failed technically (i.e., the brushes failed to remove all dirt and manure from teats before milking). Hovinen and colleagues (2005) compared 2 different types of automatic cleaning systems; the first included a cleaning cup, which used warm water, variable air pressure, and a vacuum process that dried the teats, and the second included wet rotating brushes to clean the teats from the apex to base and back. The results suggested that the brushes had better technical success compared with cleaning cups. However, the authors discovered that one-third of all cows in their trial had an unsatisfactory teat cleaning from the AMS. Important factors for technical success of the automatic cleaning process include teat and udder variation among the herd (Rodenburg, 2002; Hovinen et al., 2005), and the proportion of cows with dirty teats before milking (Dohmen et al., 2010).

One of the potential problems with AMS is their inability to discriminate between a dirty and clean udder. A more thorough udder cleaning may be necessary for some cows before milking (Dohmen et al., 2010). For example, dairy cows housed on pasture may have

cleaner udders compared than cows housed indoors (Davis et al., 2008). In an Australian study, Davis and colleagues (2008) found that eliminating teat washing for pastured dairy cattle did not increase quarter milk conductivity (means $\pm$ SE: 4,858 vs. $4,829 \pm 17$ μ S/cm for no-wash vs. wash, respectively), milk blood concentration (means $\pm$ SE: 115.7 vs. 112.3 ± 7.3 mg/kg), or test-day SCC (means $\pm$ SE: 2.044 vs. 2.039 ± 0.025 log₁₀ SCC). Similarly, eliminating washing did not affect milk yield (20.5 vs. 20.1 ± 0.2 kg for no-wash vs. wash, respectively), though greater mean quarter milk flow was observed (0.950 vs. 0.981 ± 0.013 kg/min). However, the faster milking by cows in the washed group did not counteract the time taken to wash the teats, resulting in a longer time in the AMS for cows in the washed group and an overall lower milk harvest rate (2.08 vs. 1.74 ± 0.02 kg/min crate time for no-wash vs. wash, respectively). The authors concluded that not washing teats of pastured dairy cows would potentially allow more cows to be milked per AMS without compromising milk quality or yield (Davis et al., 2008). With this in mind, it may be necessary for AMS farmers to prioritize cleanliness on their farm until a technological solution is reached that addresses the lack of ability of AMS to discriminate between dirty and clean udders, and to precisely disinfect dirty teats during cleaning.

Milk Letdown. In today's milking practices, pre-milking teat preparation is not only used to ensure clean teats before milking, but also to help stimulate milk ejection. Tactile stimulation of the mammary gland causes alveolar milk ejection through a neuroendocrine reflex arc (Bruckmaier and Blum, 1998; Dzidic et al., 2004a). Proper stimulation of the udder may be more important in AMS than in conventional parlor with twice daily milking, because short or irregular intervals can occur between milkings (Bruckmaier et al., 2001; Dzidic et al., 2004b) and teat cup attachment may fail or be delayed (Mačuhová et al., 2004).

A review by Bruckmaier and colleagues (2001) found that teat-cleaning devices in AMS were suitable for stimulating oxytocin release and milk letdown before the start of the milking process. However, because irregular intervals can occur between milkings, not all cows being milked will have udders filled to similar degrees and may need different amounts of stimulation. For example, cows with udders filled 20.1 to 60% may experience optimal milk removal after longer pre-stimulation cleaning times compared with cows whose udders are fuller (i.e., 64 s vs. ≤ 32 s of cleaning time, respectively; Dzidic et al., 2004b). Thus, programming AMS to stimulate teats based on the anticipated degree of udder fill could make milk removal more effective. Alternatively, the threshold for accepting a cow for

milking could be adjusted to accept only cows with udders expected to be >60% full (Dzidic et al., 2004b).

In AMS, there is often a pause between stimulation of the udder during cleaning and the start of milking; however, this does not seem to impair oxytocin release, milk ejection, or milk removal (Mačuhová et al., 2003), nor does the sequential attachment of teat cups by AMS, which results in a delay between the attachment of the first cup and the milking of that quarter, negatively affect milk ejection or removal (Bruckmaier et al., 2001; Mačuhová et al., 2003). Even when attachment of teat cups was delayed or only completed after several attempts, oxytocin release and milk removal were not impaired (Mačuhová et al., 2004). Additionally sequential removal of teat cups as quarters finish milking does not seem to impair milk flow by the remaining quarters (Bruckmaier et al., 2001).

Milk Leakage. It has been suggested that the constant visual and auditory stimuli from AMS could stimulate ongoing oxytocin release and milk letdown, which may increase the risk for milk leakage. Milk leakage is problematic because it places a cow at increased risk for mastitis (Waage et al., 2001). Only one published report compares milk leakage in an AMS compared with a conventional milking parlor (Persson Waller et al., 2003). The authors observed milk leakage significantly more often and in a larger proportion of cows being milked in the AMS. In an experimental study simulating the effects of failed cluster attachment, milk leakage was seen in 60% of cows following a missed milking (Stefanowska et al., 2000). However, studies examining release of oxytocin have not found increased oxytocin levels before cows entered the AMS to be milked, suggesting that milk leakage does not seem to be occurring in response to acoustic or visual stimuli associated with AMS (Bruckmaier and Blum, 1998; Bruckmaier et al., 2001; Dzidic et al., 2004b).

Klaas et al. (2005) identified teat shape, condition of teat orifice, and peak milk flow rate as risk factors for milk leakage on 15 commercial farms milking with conventional milking parlors. Milk leakage was observed and recorded in the holding area before entering the milking parlor and was defined as milk dropping or flowing from the teat. Milk leakage rates ranged from 1.2 to 12.3% across herds. Variation among cows within the herd accounted for 89.2% of the total variation in the data; milk leakage was observed in 6.1% of primiparous cows, compared with 4.8% of multiparous cows. Cows with high peak milk flow, teat canal protrusion, and inverted teat ends had increased risk of milk leakage. Additionally, intramammary pressure (IMP) has been suggested as having a strong influence on milk leakage (Rovai et al., 2007). Although IMP has yet to be assessed in an AMS, potential exists for greater variation

in milking intervals with the AMS. This may result in higher IMP in AMS, translating into additional milk leakage. Based on these results and the variation in milk leakage among herds and individual cows, it is necessary to do a more extensive study on milk leakage in multiple herds milking with an AMS to ascertain the extent of the problem. In addition, such studies should include measurements of teat end condition and previous milk leakage history to ensure accurate interpretation of the data.

MILK QUALITY

Compositional Aspects

The composition of milk in terms of protein and fat content does not appear to be influenced by the type of milking system per se (Abeni et al., 2005b, 2008), nor do the levels of lactose and urea in the milk (Friggens and Rasmussen, 2001; Hopster et al., 2002). Rather, what appears to be more important for fat content is the length of the interval since the previous milking and the variation in milk yield per milking (Bruckmaier et al., 2001; Friggens and Rasmussen, 2001).

Some evidence exists indicating that levels of FFA are increased in milk collected from farms that milk cows with AMS (Klungel et al., 2000; de Koning et al., 2004). High FFA content in milk is considered undesirable because it confers a rancid taste to the products produced from such milk. The increased milking frequency and shorter milking intervals found in AMS systems have been found to cause increased FFA content in milk (Hamann et al., 2004; Abeni et al., 2005b). In part, increased FFA may be due to low milk yields resulting from short milking intervals (Rasmussen et al., 2006). However, technical differences in handling milk between AMS farms and parlor farms, such as greater air intake during milking, may also cause some of the observed increase in FFA in AMS milk (Rasmussen et al., 2006).

Hygienic Aspects

Milk color, conductivity, and SCC can be measured automatically by AMS to help detect milk quality (although SCC measurement by AMS is not yet approved for use in the United States as a milk quality measure or indicator of mastitis). Milk color can change as a result of clinical mastitis (Kamphuis et al., 2008). Therefore, measuring the changes in color of the milk may be helpful in diagnosing potential clinical mastitis cases, although subclinical cases may go unnoticed while using this method. Electrical conductivity (EC) is one of the most common indicators used to

diagnose both clinical and subclinical mastitis and is based on measuring the increase in Na^+ and Cl^- in mastitic milk, resulting from inflammation of the udder (Hamann and Zecconi, 1998). However, according to several studies, milk EC measurement alone may not be sensitive enough to reliably detect subclinical mastitis (Hamann and Zecconi, 1998; Bruckmaier et al., 2004). For example, Hamann and Zecconi (1998) discovered only a slight change in the EC of milk with SCC levels ranging from 200,000 to 300,000 cells/mL. Electrical conductivity is not only affected by mastitis infections, but also by tissue inflammation in general, likely one of the reasons for the lack of agreement between EC and SCC (Brandt et al., 2010).

When decision trees are used to develop models for detecting clinical mastitis based on color and EC, a high degree of specificity can be obtained, although the sensitivity of such models to accurately detect mastitis remains below 70% (Kamphuis et al., 2010a,b). However, using an in-line SCC sensor (that estimates SCC based on viscosity measurements) and combining these results with EC measurements, a 3-fold improvement in detecting clinical mastitis was achieved compared with using EC alone (Kamphuis et al., 2008). Alternatively, Sun et al. (2010) demonstrated that high rates of correct classification, sensitivity, and specificity for detecting mastitis (90.74, 86.90, and 91.36%, respectively) can be obtained using a computer-based neural network model that combines information about changes in EC and milk yield within a quarter from in-line AMS sensors. Further, it may be possible to use these measures to detect the stage of progression of mastitis within the quarter (Sun et al., 2010). Thus, using a combination of available alert variables (e.g., SCC, EC, milk color, and expected milk yield) may allow the farmer to be more sensitive to potential mastitis problems (Steenefeld et al., 2010).

Somatic cell count is one of the most-used indirect indicators of subclinical mastitis, although an effect of season, parity, and lactation stage is often seen (Hamann, 2002). Several survey-based studies have examined changes in milk quality on dairy farms making the transition from conventional parlors to AMS. The findings have varied from reports of no changes or decrease in SCC (Klungel et al., 2000; Helgren and Reinemann, 2006) to increases in SCC (van der Vorst and Hogeveen, 2000; Kruip et al., 2002; Hovinen et al., 2009). In one study, Helgren and Reinemann (2006) followed the changes in SCC and total bacterial counts on 12 US farms for 3 yr after they transitioned from parlors to AMS. No initial increases in SCC or total bacterial count were found to be associated with AMS use; in fact, SCC and total bacterial counts decreased the longer the farms used AMS (Helgren and Reine-

mann, 2006). In several experimental studies comparing AMS and conventional parlors within the same farm and under the same management system, no effect of AMS has been found on udder health, including on SCC (Berglund et al., 2002; Zecconi et al., 2004; Abeni et al., 2008).

In contrast, Hovinen and colleagues (2009) found that herd SCC and proportion of new high-SCC cows was higher over the first year after introduction of AMS on 88 Finnish farms. In a survey of Dutch farms, higher test-day SCS were observed on AMS farms when assessed both between conventional and farms milking with AMS at the same time point and over time within farms that changed from conventional parlors to AMS (Mulder et al., 2004).

In general, increases in SCC and decreases in milk quality have been observed in epidemiological studies following the transition to AMS, whereas experimental comparisons have found no negative effect on udder health (see Hovinen and Pyörälä, 2011 for a review). Introduction of an AMS is often accompanied by other changes in the barn, such as changes in teat cleaning, cow groups, stall type, manure handling, and general herd management and there may be increased reliance on automatically gathered data. A recent study conducted on 144 Dutch dairy farms milking with an AMS for at least 1 yr indicated a direct positive relationship between cow hygiene, successful disinfection of the teats before milking, and SCC (Dohmen et al., 2010). Until further technical development occurs (particularly in regard to discriminating between clean and dirty teats, and automatically detecting mastitis), farm priorities should include careful observation of cow cleanliness and udder health (Hovinen and Pyörälä, 2011).

PASTURE-BASED SYSTEMS

As dairy farmers worldwide increasingly accept AMS, there is growing interest in successfully combining AMS with pasture-based systems, particularly in Europe, Australia, and New Zealand. Although few researchers have explored this area, initial studies have identified both benefits and obstacles to incorporating a combined AMS-pasture system.

As mentioned previously, one of the main differences between AMS and conventional parlor systems is the reliance on the cows to go voluntarily, and individually, to the milking unit several times daily to be milked (Spörndly and Wredle, 2005). Therefore, it is important to understand the motivations and mechanisms that can effectively induce cows with access to pasture to return to the AMS to maintain the desired number of visits. Spörndly and Wredle (2005) suggest that voluntary milking frequency decreases to some extent when cows

are turned out to pasture. In their survey involving 25 farms that combined AMS and grazing systems, the authors ascertained that 0.2 fewer milkings per cow per day occurred during the farms' pasture months compared with their indoor months (determined seasonally). Experimental studies have reported ranges of 1.4 to 2.3 milkings per day for grazing cows, with higher rates for cows receiving forage in the barn compared with 100% grazing systems (Ketelaar-de Lauwere et al., 1999; Jago et al., 2007; Davis et al., 2008).

However, a slight decrease in milking frequency may be natural, as energy intake decreases with a 100% pasture-based diet. To maximize the use of AMS in pasture dairies, it may be more effective to decrease the number of milkings expected per cow and increase the number of cows per AMS (Jago et al., 2007). When the milking interval of pastured cows increased from 12.6 to 16.90 h, the milk collection rate increased from 1.18 to 1.63 kg/min, respectively, but milk yield was not affected (22.78 to 23.27 kg/d). This indicates that more cows could be milked per AMS without negatively affecting the milk production of individual cows, thus increasing overall production yield per AMS (Jago et al., 2007).

When AMS are combined with grazing, a well-functioning cow traffic system becomes essential to the success of the farm due to the increased distances between the AMS and feed source (i.e., pastures; Wiktorsson and Spörndly, 2002), and because cow behavior is more synchronized on pasture compared with behavior in indoor housing systems (Ketelaar-de Lauwere et al., 1999; Ketelaar-de Lauwere and Ipema, 2000; Tucker et al., 2008). In a study by Ketelaar-de Lauwere et al. (1999), cows were only seen alone on pasture in 0.4 to 2.8% of cases and alone in the barn during 9.7 to 12.7% of observations. Cows were also observed entering and leaving the barn in the company of other cows in 76.6 and 90.7% of the cases, respectively, likely as a result of social facilitation (Ketelaar-de Lauwere et al., 1999). Thus, without a well-managed traffic situation, the potential for a bottleneck or absence of cows at the AMS increases, resulting in a less efficient milking system (Wiktorsson and Spörndly, 2002).

Wiktorsson and Spörndly (2002) found that one-way gates at the barn entrance and selection gates at the exit from the barn to the pasture were successful at optimizing cow traffic when an AMS was used in conjunction with a pasture-based system. Alternatively, a system where the exit to the pasture can be reached only after passing the milking unit appears to be a way to limit the number of animals needing to be fetched to the AMS (Jago et al., 2004; Spörndly and Wredle, 2004). Simply increasing permitted milking frequency may also be enough to cause an increase in the number

of milkings per day (Jago et al., 2007). In addition to using cow trafficking systems, cows could be trained by operant conditioning to return to the barn from pasture in response to an acoustic signal (Wredle et al., 2006). Innovative motivations like this may help to encourage cows to return to the barn and maintain milking frequency. However, potential challenges are associated with such techniques; for example, motivating the return of all cows simultaneously could create a large queue of cows standing in the waiting area.

Limiting water availability to the barn has been suggested as a way to further stimulate cows to voluntarily return from pasture to be milked (Spörndly and Wredle, 2004, 2005). However, relatively high levels of moisture in pasture forage may decrease the effectiveness of water as a motivator when pastures are lush. Importantly, such a strategy could limit water intake, decreasing cow welfare and milk production (NRC, 2001). Based upon a study conducted by Spörndly and Wredle (2005), which compared a group of cows with unlimited water access and a group with access to water only in the barn, no significant differences were seen in milk yield, milking frequency, or water intake between the 2 groups.

Another area of concern when combining AMS and grazing is the distance between the pastures and the barn. Ketelaar-de Lauwere and colleagues (2000b) found no significant differences between animals walking a short distance to the barn (150 m) compared with a longer distance (350 m) with regard to milking frequencies and total number of visits to the milking unit. However, Spörndly and Wredle (2004) found that cows walking a longer distance (260 m compared with 50 m) had both a lower milk yield and milking frequency.

It is worthwhile to mention the importance of understanding animal behavior and production as it pertains to combined pasture and automatic milking systems. The grazing season is characterized by constant changes in weather, pasture supply, pasture quality, and day length. Compared with systems where cows are housed indoors and fed TMR, cows at pasture with an AMS can and do respond to varying environmental conditions (Ketelaar-de Lauwere and Ipema, 2000; Wiktorsson and Spörndly, 2002). Therefore, it becomes more important to understand how dairy cow behavior can be influenced by these different factors. Cows with unrestricted access to pasture and barn preferred to be in the barn during the middle of the day, when the conditions for heat stress were highest, and on pasture overnight (Ketelaar-de Lauwere et al., 1999). In this study, the cows also spent 80.0 to 99.9% of their total lying time on pasture (Ketelaar-de Lauwere et al., 1999). Research from the Greenfield project suggests that cow traffic to the barn begins around sunrise and remains relatively constant throughout the day, with

the exception of a lull between the hours of 0200 and 0600 (Woolford et al., 2004). The authors mention, however, that activity depended on the time at which a fresh pasture break was available or on weather conditions, making it important to take these factors in consideration when attempting to maximize visits to the barn evenly over 24 h. Additionally, these factors must be considered when determining the number of grazing cows that can be supported by a milking stall, and the ideal number may change throughout the year.

A high level of supplementation in the barn and a more limited pasture area have been suggested to have a positive influence on cow motivation to return to the barn from pasture. Cows may spend as little as 15% of their day outdoors with little grazing activity when offered a significant amount of high-quality concentrates indoors (Karlsson, 2001). In addition, sward height has been shown to have an effect on milking frequency and cow behavior. In a study by Ketelaar-de Lauwere and colleagues (2000b), sward height was measured as it decreased from 11–12 cm to 7–8 cm in a grazing pasture. The authors noted that as sward height decreased, cows spent more time in the barn, and the number of visits to the AMS increased.

Greenall and colleagues (2004) suggest that the key to motivating cows to visit AMS in a pasture system is flexible farm management and a broad understanding of cow behavior and dietary needs. Thus, in grazing situations, managers need to constantly evaluate and manipulate the cow's access to the various dietary components available to make the farm successful. Certainly, more research on the combination of AMS with grazing systems is needed if the combination is to be more widely considered by farmers around the world.

DIRECTIONS FOR FUTURE RESEARCH

Automatic milking systems have been available commercially in Europe since 1992, and were adopted by more than 8,000 farms by the end of 2009 (de Koning, 2010). Since then, researchers have assessed AMS' affect on milk production, labor costs, and welfare of the dairy cow. Although a large amount of general research on these subjects has been completed, greater depth is needed as many questions about AMS still remain.

Little experimental work has been conducted using stocking rates of cows per AMS, stalls and feed bunk that are common in commercial practice. Further, little work has been conducted specifically in North America using breeds and group sizes more typical for the region. As group size and stocking rates change on AMS farms, it is possible that many of the reported behaviors and production outcomes also change. Strategies for optimizing AMS use through changing the number

of cows milked per AMS should be explored; for example, on pasture it may be more feasible to increase milk production by increasing the number of cows per AMS rather than the number of milkings per cow. Experimental manipulations of group size, group composition, the number of cows per AMS, the number of lying stalls per cow, and the amount feed bunk space per cow should be undertaken to optimize AMS barn design and herd management. A more complete understanding of diurnal patterns of feeding, lying, and milking behavior in AMS is needed, as well as of the effects of human management actions on behavior. Further, differences between primiparous and multiparous cows related to adaptation, use of AMS, and the effect of social interactions on welfare should be explored, as some evidence suggests that differences exist between older and younger cows.

Some researchers are skeptical that dairy cows are able to act independently from others in the herd, decreasing the efficiency of the AMS by creating bottlenecks at the entry to the milking stall, when all cows approach at once, or an idle milking unit at other times. An AMS relies on continuous usage to maintain its productivity and value to the farm. Although anecdotally this situation has been contradicted, it is important that it is explored and documented scientifically. Thus, work examining cow traffic needs to be continued, particularly with regard to how individual cow and group behavior affect AMS use. Understanding why some cows spend significant amounts of time in unsuccessful visits to the AMS or in blocking AMS exits rather than lying or feeding may result in strategies that improve use of cow behavior and motivation to benefit both cows and producers.

Though several researchers have examined the effect of cow traffic systems, questions still remain about how best to optimize cow flow through the system. As the presence of cows near the AMS appears to affect efficient exit from and entry to AMS, this phenomenon, and ways to mitigate it, deserve more attention. A few researchers have suggested that decreasing the number of turns cows must make in selection and waiting areas may enhance cow movement through AMS. Some recent AMS stalls open at the front and rear (rather than the side) to allow cows to enter and exit the milking stall in a straight line, without turning or bending their bodies. It would be interesting to study whether these changes result in more efficient cow movement in and out of such milking stalls in comparison with other designs.

Dairy farmers have indicated that the number 1 reason for investing in an AMS was the potential savings in labor. However, a reduction in labor is not always possible due to a substantial number of cows that need

to be fetched to the AMS each day. Cows needing to be fetched to the AMS may have problems with mobility or lameness (Borderas et al., 2008). An AMS offers a unique possibility to automatically detect lameness. By separately measuring the load on each leg when the cow is standing in the milking stall and integrating this information with data from activity monitors, it likely AMS could identify cases of subclinical lameness, potentially before problems become evident in gait (Pastell et al., 2006). This would not only be beneficial for identifying lame cows automatically, but it also may prove to be a predictor for cows that have an increased likelihood of requiring fetching.

However, in cases where lameness is not the culprit, fetching may be indicative of a negative association with the AMS or herds person or a lack of motivation for cows to independently approach the milking unit without assistance from human caregivers. These other factors require additional attention from researchers to develop solutions to reduce the need for fetching. For example, if cows voluntarily milk less often because they are afraid of human handlers (Rousing et al., 2006), programs could be devised to promote positive human-animal interactions and reduce cow fear.

There is some indication that cows in AMS experience more chronic stress than cows in parlor systems. However, much of this work has been conducted in forced or guided traffic situations and with small experimental herds that do not mimic commercial conditions. Additional data should be collected from commercial farms transitioning to AMS or between matched AMS and parlor farms to examine the welfare of AMS cows in production settings.

Rousing and colleagues (2007) have developed a protocol for assessing the welfare of cows in AMS herds with input from researchers, production advisors, and veterinarians. The welfare indicators most highly prioritized included features of housing systems (cubicles, indoor climate, and surfaces and materials), management routines (stocking rate and cleaning and bedding), cow health (lameness, dirtiness, BCS, and pressure sores), and behavior (during milking and when getting up). However, these indicators should be validated in the field to demonstrate that they do in fact provide information about cow welfare; then, protocols can be developed for performing assessments using the most informative and reliable measures.

Little research has characterized the metabolic and immune responses of dairy cows milked in AMS. Although some evidence exists that cows in AMS do not experience negative energy balance despite more frequent milking, the limited nature of the existing studies do not provide definitive conclusions (Abeni et al., 2005b, 2008). More information is needed regarding

changes in early lactation, cows of higher parities, cows of varying production potentials, and effects of typical production settings.

The wide range of sensors associated with AMS should be studied more fully to elucidate their ability to accurately detect important changes in cow health, behavior, and welfare, including estrus, lameness, and feeding changes that might signal health problems. Additionally, protocols aimed at using in-line sensors and computer models to detect mastitis need to be tested on farm to verify their utility. Technological improvements in cluster attachment and identification and cleaning of dirty udders need to continue and their effectiveness examined to optimize cow health and milk quality. Further studies on milk leakage should be conducted to determine whether this is truly a problem for cows in AMS systems. Milk handling and methods for motivating cows to milk regularly at desired intervals should be explored to decrease FFA levels found in AMS milk. Management programs should take advantage of the large amount of data available to determine the best milking frequency for each individual cow to maximize her individual production and the herd's use of the AMS.

Studies examining combined AMS and pasture systems suggest that entirely different AMS optimization strategies may be needed to successfully combine the systems. Changes in cow behavior on pasture coupled with changes in energy balance and anticipated milk yield suggest that higher stocking rates, different motivations to encourage cows to milk, and effects of weather in AMS pasture systems are topics requiring further attention.

As stated previously, differences in management may underlie the contradictory results sometimes seen in studies examining AMS. For example, differences in lameness, estrus detection, BCS, udder health, and milk quality between AMS and conventional parlor systems may not necessarily be due to changes in milking systems. Rather, the disparity between results may be more closely associated with differences between management and facility design. Future research should be conducted with this deliberately in mind. Perhaps a future goal may be to identify flexible management techniques that can be applied to farms with AMS to help ensure success for both the farm staff and cows during the transition and beyond.

Although AMS have been widely adopted in Europe, it has yet to be determined if they are well-suited to US conditions. A survey of farmers who have implemented AMS for several years may be beneficial to understanding their overall worth. Several different factors will influence the success and value of AMS, including understanding dairy cow motivation and the

social dynamics of the herd, as well as decreasing the number of cows needing to be fetched to the AMS, subsequently decreasing labor costs. It is important for research to continue in these areas if the AMS is to become a successful milk production unit for farms of all sizes and locations.

CONCLUSIONS

Over the past few decades, many changes have occurred in the dairy industry. The introduction of automation in milking has generated a great deal of anticipation for the newest milking advancement in the dairy industry. Much of the focus of research on AMS has mirrored consumer interest in milk production, labor, welfare, health, and milk quality; however, more depth and detail is needed, especially as it becomes clear that management continues to play a huge role in the success or failure of the AMS. With so many contradicting results, the need for expanded research is apparent.

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