Comparison of Functional Aspects in Two Automatic Milking Systems and Auto-Tandem Milking Parlors

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ABSTRACT

Milk yield, milking frequency, intermilking interval, teat-cup attachment success rate, and length of the milking procedure are important functional aspects of automatic milking systems (AMS). In this study, these variables were compared for 2 different models of AMS (AMS-1, with free cow traffic, and AMS-2, with selectively guided cow traffic) and auto-tandem milking parlors (ATM) on 4 farms each. Data on milking-stall visits and milkings of 20 cows were recorded on 3 successive days by means of video observations. Data were evaluated with mixed-effects models. Milk yield did not differ among the 3 milking systems. Milking frequency in the AMS was 2.47/d [95% confidence interval (CI) = (2.38, 2.56)], and was significantly higher than the 2 milkings/d in ATM. Milking frequency was lower for cows with a higher number of days in milk (DIM) in AMS-1 [change of $-0.057/10$ DIM, CI = (-0.070 , -0.044)], but remained constant for cows with varying DIM in AMS-2 [change of $-0.003/10$ DIM, CI = (-0.034 , 0.027)]. As a consequence, milking frequency was higher in early lactation [by 0.603, CI = (0.102, 1.103)] and lower in late lactation in AMS-1 than in AMS-2 [by -0.397 , CI = (-0.785 , -0.008)]. The intermilking interval showed the opposite pattern. Teat-cup attachment was more successful in AMS-1 than in AMS-2 (98.4 vs. 94.3% of the milkings), with some variation among farms (range: AMS-1 96.2 to 99.5%; AMS-2 91.5 to 96.1%). The length of the entire milking process did not differ among the milking systems [454 s, CI = (430, 478)], although the preparation phase was longer [changes in comparison with ATM: in AMS-1 by a factor of 2.90, CI = (2.30, 3.65), and in AMS-2 by 5.15, CI = (4.09, 6.48)] and the actual milking phase was shorter in both AMS-1 and AMS-2 than in ATM [changes in comparison with ATM: in AMS-1 by a factor of 0.76, CI = (0.62, 0.94), and in AMS-2 by 0.75, CI = (0.60, 0.93)]. The admission [changes in comparison with ATM: in

AMS-1 by a factor of 2.56, CI = (1.55, 4.22), and in AMS-2 by 3.07, CI = (1.86, 5.08)] and preparation phases lasted longer in AMS-2 than in AMS-1, whereas the time required by the cows to leave the milking stall did not differ among the systems [changes in comparison with ATM: in AMS-1 by a factor of 0.89, CI = (0.55, 1.44), and in AMS-2 by 1.02, CI = (0.63, 1.66)]. In conclusion, different technical approaches to automatic milking led to differences in teat-cup attachment success rates, in the duration of several phases of the milking process, and in milking frequency. The capacity of an AMS could be further improved by shortening the preparation phase and reducing the proportion of failed milkings.

Key words: dairy cow, automatic milking system, teat-cup attachment success, milking phase

INTRODUCTION

Increased milking frequency in conventional milking parlors increases milk yield (Barnes et al., 1990), whereas automatic milking systems (AMS) free the farmer from set milking times. From a technical point of view, the most important functional difference between AMS and conventional milking parlors is the automatic teat-cup attachment process, which is controlled in AMS by ultrasonic, laser, or optical sensors (Artmann, 1997). Consistent and reliable teat-cup attachment is crucial for the success of any AMS-equipped farm. Malfunctions of this process may lead to milk leakage (Persson Waller et al., 2003), because udder stimulation leads to the onset of milk ejection. Milk leakage is a risk factor for mastitis (Stefanowska et al., 2000; Waage et al., 2001) because of germ proliferation at the teat orifice (Rémond et al., 2002).

Failed milkings should be avoided on economic grounds, because unsuccessful teat-cup attachment reduces the capacity of an AMS (Kaufmann et al., 2001). Similarly, the lengths of different phases of the milking process have an impact on AMS capacity; for example, an increase of 0.5 min in the average handling time (walking in and out of the system, identification, udder preparation, and attachment of teat cups) lowers the

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milking capacity of an AMS by 5 to 8% (De Koning and Ouweltjes, 2000). Differences in handling time are caused by characteristics of the individual cows (e.g., udder shape) that influence the length of the teat-cup attachment process (Huschke and Klimetschek, 2000; Macuhova et al., 2004), as well as by systematic differences among different AMS models in the time required to clean the teats and attach the teat cups (Hvaale et al., 2002).

In the past, studies on milk yield (Abeni et al., 2005), the success of teat-cup attachment (Huschke and Klimetschek, 2000), and the lengths of different phases of the milking process (Hvaale et al., 2002; Hagen et al., 2004) were conducted on individual farms run for the most part under experimental conditions and having a low number of cows. The aim of the present study was to collect data on these functional aspects for 2 AMS models on 4 farms, which were operated under commercial conditions, and to compare these results with data from 4 farms that used auto-tandem milking parlors (ATM).

MATERIALS AND METHODS

Milking Systems, Animals, and Farms

A total of 12 Swiss farms were investigated. Each of the farms was equipped with either of 2 AMS models (AMS-1: Lely Astronaut, Lely Industries N.V., Maassluis, the Netherlands; AMS-2: DeLaval Voluntary Milking System, DeLaval International AB, Tumba, Sweden), or with an ATM (three 2 × 2 and one 2 × 3; DeLaval, Tumba, Sweden, and Westfalia, WestfaliaSurge GmbH, Oelde, Germany). Auto-tandem milking parlors were chosen for comparison on the basis of their similarity to AMS (individual milking stalls, individual entry to and exit from the milking stalls). At the time of investigation, the milking systems had been operative for at least 6 mo. The AMS farms were chosen according to the manufacturers' recommendations.

All farms were free-stall housing systems equipped with at least as many free stalls as cows. On farms with AMS-1, free cow traffic with unrestricted access to lying and feeding areas was implemented. Three of these farms had a waiting area in front of the milking unit, which was reached through a one-way gate and which, contrary to Swiss animal welfare regulations, was the only place where water was provided. On one farm, the restriction applied only during the summer, whereas on another farm, cows had access to water through the waiting area fence at all times. On farms with AMS-2, selectively guided cow traffic was used with selection gates between the lying and the feeding areas, thereby forcing cows that had not been milked within the time interval specified by the manufacturer's software to ac-

cess the feeding area through the AMS. On 2 of these farms, selection gates of this type were available only in the waiting area in front of the milking unit. On all AMS farms, cows that had not been milked for 8 h or more were fetched once or twice daily.

Both AMS investigated were one-box systems. The 2 AMS models differed in design of the robot arm: in AMS-1 the arm held the teat-cleaning brushes, the teat-location device, and the teat cups, whereas only the teat-location system was mounted on the service arm of AMS-2. The teat-cleaning cup and teat cups were obtained in succession from a mounting at the side of the milking stall in AMS-2. Teat cups were removed 1 quarter at a time in both AMS models on the basis of milk flow, whereas the whole milking cluster was removed at the same time in ATM. In AMS-1, the floor of the milking stall was made of metal (with a profiled surface), whereas a rubber mat was used in AMS-2. Automatic milking system-1 had an electric exit drive, which was deactivated because of a ban on such equipment in Switzerland, and AMS-2 had a working pressurized-air jet to prompt cows to leave the milking box. Unlike in the ATM, cows were fed part of their daily concentrate feed ration in both AMS.

Breeds consisted mainly of types selected for high milk yield (AMS-1: 3 herds were mainly Brown Swiss and 1 was mainly Red Holstein; AMS-2: 2 herds were mainly Holstein-Friesian, 1 was mainly Red Holstein, and 1 was mixed Brown Swiss-Red Holstein; ATM: 2 herds were mainly Brown Swiss, 1 herd was mainly Holstein-Friesian, and 1 herd was Swiss Simmental).

For the investigation, a sample of 20 focal cows was selected from each herd (Table 1). To reduce variation in the data between farms, because cows are known to have problems coping with the milking system, the focal cows were selected with the assistance of the farmer. Cows that regularly showed nervous behavior during milking as well as those with health problems were not used. It was necessary to reduce the sample on 2 of the farms to 18 and 16 cows, respectively.

The investigations took place in autumn to winter of 2001 to 2002, spring of 2002, and autumn to winter of 2002 to 2003. In the first 2 data collection periods, 1 farm was visited per system (farms A, E, and J, and farms B, F, and H), and in the last period 2 farms were visited per system. Data were collected in one of the periods for 3 consecutive days.

Measurements

Twenty-four-hour video recordings were used for classifying the milkings and for measuring the length of the different milking phases. A camera focused on the udder and hind legs was installed in the AMS itself. On the

Table 1. Herd size on the study farms (A to L) and characteristics of the focal cows observed in 2 types of automatic milking systems (AMS-1, AMS-2) and auto-tandem milking parlors (ATM)

Milking system	Farm	Herd size (n)	Focal cows (n)	Focal cow characteristic		
				Parity (mean $\pm$ SE)	DIM (mean $\pm$ SE)	Daily milk yield (L/d)
AMS-1	A	39	20	3.8 $\pm$ 0.4	140 $\pm$ 22	17.5 $\pm$ 1.4
	B	49	20	4.0 $\pm$ 0.5	174 $\pm$ 12	22.4 $\pm$ 1.8
	C	49	20	2.7 $\pm$ 0.3	130 $\pm$ 16	30.7 $\pm$ 2.1
	D	47	20	2.7 $\pm$ 0.3	149 $\pm$ 20	25.7 $\pm$ 2.4
AMS-2	E	50	20	2.7 $\pm$ 0.4	165 $\pm$ 26	23.5 $\pm$ 2.1
	F	47	20	2.4 $\pm$ 0.4	184 $\pm$ 17	23.0 $\pm$ 1.3
	G	56	20	2.9 $\pm$ 0.4	173 $\pm$ 23	23.4 $\pm$ 1.6
	H	30	18	2.2 $\pm$ 0.3	177 $\pm$ 19	15.3 $\pm$ 1.3
ATM	I	26	20	3.3 $\pm$ 0.4	91 $\pm$ 15	24.4 $\pm$ 2.1
	J	21	16	2.4 $\pm$ 0.4	180 $\pm$ 21	24.1 $\pm$ 1.0
	K	43	20	2.6 $\pm$ 0.3	204 $\pm$ 21	21.5 $\pm$ 1.6
	L	22	20	2.4 $\pm$ 0.4	126 $\pm$ 13	23.7 $\pm$ 1.7

farms with ATM, up to 4 cameras were installed in the milking parlors to allow simultaneous observation of all milking stalls. The video recordings were analyzed with a software program that combined the time signal from the video recorder with manually entered codes for the different milking phases (Etho, R. Weber, Agroscope Reckenholz-Tänikon Research Station ART, Tänikon, Switzerland).

Each milking was judged as successful or failed. Failed milkings were those in which the teat-cup attachment process required assistance from the farmer, those in which the teat-cup attachment process was unsuccessful for at least 1 of the 4 teats, or those in which all teat cups were successfully attached initially but with 1 or more immediately kicked off or falling off, followed by unsuccessful attempts at reattachment.

The length of different milking phases was calculated on the basis of the video recordings. The data were differentiated into the admission phase (time lag between the closing of the entrance gate and the onset of preparation), the preparation phase (first tactile contact between the animal and the milking system or milker until successful attachment of all teat cups, i.e., cleaning and teat-cup attachment), the milking phase (end of teat-cup attachment until removal of the last teat cup), and the exit phase (removal of the last teat cup until all 4 legs were outside the milking stall). Preparations included both teat cleaning and teat-cup attachment, because the relative positioning of the cameras and the milker made it impossible to distinguish between these 2 actions on farms with ATM. In addition, the sum of these phases was evaluated as the overall length of milking. On the basis of the same data, intermilking intervals were calculated as the time between visits to the milking stall at which milking was attempted, regardless of the actual success of the attempt.

In both the AMS and the ATM, milk yield was recorded automatically and stored in the management system. For each focal cow, average daily milk yield was calculated by dividing the total milk yield by the length of the video recordings on a given farm, and average daily milking frequency was calculated by dividing the total number of successful milkings during the observation period by the same duration.

Statistical Analysis

Milk yield, milking frequency, intermilking interval, length of the entire milking, and lengths of the admission phase, preparation phase, milking phase, and exit phase were used as response variables in different linear mixed-effects models (Pinheiro and Bates, 2000; Pinheiro et al., 2006) calculated by using a restricted maximum-likelihood approach in R 2.3.1 (R Development Core Team, 2006).

Where data on the individual milkings were included in the analyses (intermilking interval, phase lengths), milking system, farm, and individual cow were included as nested random effects to account for repeat milkings of cows and the potential dependency among cows on each farm. For data at the individual-cow level (milk yield, average milking frequency), the random effects consisted of farm nested in milking system.

Milking system (2-level factor, AMS-1 vs. AMS-2, or 3-level factor, AMS-1 vs. AMS-2 vs. ATM; treatment contrast with AMS-1 or ATM as the reference level), parity (continuous), and DIM (continuous) were included as fixed explanatory variables in all statistical models. Average milk yield was highly correlated with DIM, and was not included as an independent explanatory variable along with DIM. Explanatory variables with significant

effects on the response were identified by using a stepwise backward procedure.

A likelihood-ratio test was used in all models to check whether a term allowing for different variability in the 2 (or 3) milking systems included in the given analysis led to a significant improvement of the model. This addition to the model had to be included for most phase durations, and was thus included for the sake of consistency in all analyses of length of the different phases. For the other models, the statistical term for variability in the milking systems is mentioned in the results if it led to an improvement of the model.

Assumptions (normality and homoscedasticity) of the models were checked by graphical analysis of the residuals. To meet statistical assumptions for right-skewed measurements, most response variables (milk yield, length of the complete milking, lengths of the admission, preparation, milking, and exit phases) were log-transformed. In the models of the length of the different phases, a few outliers had to be excluded to meet statistical assumptions (admission phase: 2 milkings in AMS-1, 1 milking in AMS-2; preparation phase: 1 milking in AMS-1; exit phase: 1 milking in AMS-1, 3 milkings in AMS-2). The omission of the outliers had no major impact on model estimates or on *P*-values.

A total of 2,323 visits (AMS-1: 843; AMS-2: 763; ATM: 717) to the milking stalls of 234 focal cows (AMS-1: 80; AMS-2: 78; ATM: 76) were recorded. An attempt was made to include as many observations as possible in all the different statistical evaluations. The 2 cows for which milk yield was not available were excluded from the analyses of milk yield, milking frequency, and intermilking interval. Thus, the sample size for the milk yield evaluation was 232 cows (AMS-1: 80; AMS-2: 77; ATM: 75) and was 157 cows (AMS-1: 80; AMS-2: 77) for milking frequency. All cows in the AMS were used for assessing teat-cup attachment success if the process was clearly visible on the video (158 cows: AMS-1, 80; AMS-2, 78; 1,263 visits: AMS-1, 692; AMS-2, 571). In the analysis of the intermilking interval, we included all milkings of the 157 cows in the AMS with milk-yield data for which the previous milking had been observed (1,294 milkings: AMS-1, 685; AMS-2, 609). No successful milkings were recorded for 9 of the 234 focal cows, nor could the different milking phases be properly observed in some milkings. Thus, the sample size for the length of the different milking phases was reduced to 1,550 milkings (AMS-1, 658; AMS-2, 487; ATM, 405) of 225 cows (AMS-1, 80; AMS-2, 72; ATM, 73).

In addition, milking frequency minus 2 was used as a response variable in a model with only an intercept to test whether the average milking frequency in the AMS differed from the 2 milkings per day performed in the ATM. To better understand the interaction between DIM

and type of AMS, the milking frequency and the intermilking interval in the 2 types of AMS were compared in early (<100 DIM, 46 cows with 428 milkings) and late (>200 DIM, 55 cows with 392 milkings) lactation.

The proportion of successful milkings per farm was compared between the 2 types of AMS by using a Mann-Whitney U-test (test statistic *U*). Several other farm-level measurements were compared between the AMS by using the same test, or were compared among all 3 milking systems by using a Kruskal-Wallis test (test statistic *H*).

RESULTS

Milk Yield, Milking Frequencies, and Intermilking Intervals

For the focal cows, daily milk yield during the investigation did not differ among the milking systems (Table 1; $F_{2,9} = 0.36$, $P = 0.71$). Mean milk yield was lower in cows with higher DIM [by a factor of 0.97/10 DIM, 95% confidence interval (CI) = (0.966, 0.973), $F_{1,218} = 247.58$, $P < 0.001$] and was higher in those of higher parity [by a factor of 1.02, CI = (1.00, 1.04), $F_{1,218} = 4.29$, $P = 0.040$].

An average daily milking frequency of 2.5 was found (range: 0.8 to 3.9 per cow) on farms with AMS-1 and a frequency of 2.4 (range: 1.2 to 3.6) was found on farms with AMS-2. These milking frequencies were estimated at an overall average of 2.47/d [CI = (2.38, 2.56)], and were higher than 2 milkings per day as found in ATM [(constant predefined value of 2 milkings per day) $F_{1,149} = 103.04$, $P < 0.001$]. When evaluated in greater detail, milking frequency was lower in cows with higher DIM in AMS-1 [change of $-0.057/10$ DIM, CI = (-0.070 , -0.044)], whereas the number of milkings was almost constant with DIM in AMS-2 [change of $-0.003/10$ DIM, CI = (-0.034 , 0.027)]; interaction between milking system and DIM: $F_{1,147} = 36.96$, $P < 0.001$; Figure 1A]. When looking specifically at cows in early and late lactation, the former visited the milking stall more often in AMS-1 than in AMS-2 [by 0.603, CI = (0.102, 1.103); $F_{1,6} = 8.69$, $P = 0.026$], whereas the latter visited the milking stall less often in AMS-1 than in AMS-2 [by -0.397 , CI = (-0.785 , -0.008); $F_{1,6} = 6.25$, $P = 0.046$].

Intermilking intervals had the opposite pattern of milking frequency (interaction between milking system and DIM: $F_{1,147} = 17.96$, $P < 0.001$; Figure 1B). Accordingly, intermilking intervals were shorter in AMS-1 for cows in early lactation [by -88.96 min, CI = (-172.88 , -5.04); $F_{1,6} = 6.73$, $P < 0.041$] and longer for those in late lactation [by 79.31 min, CI = (1.30, 157.33); $F_{1,6} = 6.19$, $P < 0.047$] than in AMS-2. Variability in the intermilking intervals was 16% greater in AMS-2 than in AMS-1 (likelihood ratio: $\chi^2_1 = 12.37$, $P < 0.001$). Extremely short

Figure 1. Influence of DIM on (A) milking frequency (number of milkings per day) and (B) intermilking interval (in hours) in 2 types of automatic milking systems (AMS-1, AMS-2) on 4 farms each (identified by different symbols). Points in panel A reflect individuals and in panel B single milkings; most data points shown on the same day into milk belong to a single cow. Symbols are darker with increasing average daily milk yield. Thick lines: model prediction; thin lines: 95% confidence interval.

intermilking intervals with lengths of <3 h were observed in only 13 milkings (1.0%), mostly when cows revisited the AMS shortly after a failed milking. Milking intervals longer than 20 h were found for 3 cows, all in late lactation. The majority of milking intervals lasted between 6 and 12 h (66% in AMS-1, 69% in AMS-2; $U = 7$, $P = 0.89$; Table 2). Although the percentage of milking intervals shorter than 6 h was fairly low (14% in AMS-1, 8% in AMS-2; $U = 13$, $P = 0.20$), a larger percentage lasted longer than 12 h (20% in AMS-1, 23% in AMS-2; $U = 6$, $P = 0.68$; Table 2). Neither these percentages nor the

total number of milkings per farm and day differed between the 2 types of AMS ($U = 8$, $P = 1.00$; Table 2).

Teat-Cup Attachment Success

The percentage of successful teat-cup attachments, and hence milkings, for the focal cows was higher in AMS-1 (97.8%) than in AMS-2 (93.5%; $U = 16$, $P = 0.03$; Table 2). The same pattern was found when only milkings that failed for technical reasons (and not owing to the cow's behavior, e.g., kicking) were taken into account,

Table 2. Characteristics (median and range over 4 farms each) for intermilking intervals, teat-cup attachment success, and milking phase lengths in 2 types of automatic milking systems (AMS-1, AMS-2) and auto-tandem parlors (ATM)

Variable	Milking system		
	AMS-1	AMS-2	ATM
Intermilking intervals <6 h (%)	13.5 (6–23)	9.5 (3–16)	—
Intermilking intervals 6–12 h (%)	65.5 (58–77)	69 (61–83)	—
Intermilking intervals >12 h (%)	19.5 (16–23)	22.5 (13–23)	—
Milkings/d, all cows (n)	122 (90–125)	118.5 (72–132)	—
Teat-cup attachment success, focal cows (%)	99 (96–100)	95.5 (92–96)	—
Teat-cup attachment success, focal cows, technical (%)	97.5 (96–100)	94.5 (92–95)	—
Proportion of focal cows with unsuccessful milkings	15 (5–20)	34.5 (10–50)	—
Teat-cup attachment success, all cows (%)	96.5 (95–99)	91 (89–94)	—
Median length of unsuccessful milkings, focal cows (s)	348 (269–455)	497.5 (385–521)	—
90% quantile, length of preparation phase (s)	122.5 (110–125)	82.5 (175–250)	40 (30–80)
Maximum length of preparation phase (s)	311.5 (243–617)	324 (207–358)	79 (71–144)
90% quantile, length of exit phase (s)	21 (18–44)	27 (17–38)	29.5 (17–41)

with 98.4% of milkings in AMS-1 compared with 94.3% of milkings in AMS-2 being successful ($U = 16$, $P = 0.03$; Table 2). Although the unsuccessful milkings were distributed over a smaller overall proportion of focal cows in AMS-1 (11%) than in AMS-2 (31%), the difference did not reach significance because of a large variability among farms ($U = 2.5$, $P = 0.14$; Table 2). The management software of the 2 AMS models recorded a higher proportion of successful milkings for all cows in AMS-1 than in AMS-2 (97.5% compared with 89.7%; $U = 16$, $P = 0.03$; Table 2). In the ATM, all teat-cup attachments were successful. Milking-stall occupation times (time of entry until time of exit) during failed milkings was similar in both AMS, with a median of 377 s in AMS-1 (range 208 to 1,276) and 469 s in AMS-2 (range 47 to 1,530; $U = 2$, $P = 0.11$; Table 2).

Length of the Milking Phases

There was no evidence supporting differences in the length of the entire milking process among the different systems [overall mean duration 454 s, CI = (430, 478); changes in comparison to ATM: by a factor of 0.92, CI = (0.83, 1.03) in AMS-1 and by 1.07, CI = (0.95, 1.20) in AMS-2; $F_{2,9} = 2.26$, $P = 0.16$; Figure 2], although the process was shorter for cows with higher DIM [by a factor of 0.994/10 DIM, CI = (0.991, 0.998); $F_{1,211} = 10.60$, $P = 0.001$] and longer for those of higher parity [by a factor of 1.03, CI = (1.01, 1.05); $F_{1,211} = 12.19$, $P < 0.001$].

The admission phase was longest in AMS-2, closely followed by AMS-1, and was shortest in ATM [changes in comparison with ATM: by a factor of 2.56, CI = (1.55, 4.22), in AMS-1 and by 3.07, CI = (1.86, 5.08), in AMS-2; $F_{2,9} = 14.05$, $P = 0.002$; Figure 2). Moreover, it was shorter for cows of higher parity [by a factor of 0.98, CI = (0.97, 0.996); $F_{1,212} = 10.57$, $P = 0.001$]. The length of the

preparation phase decreased from AMS-2 to AMS-1 and ATM [changes in comparison with ATM: by a factor of 2.90, CI = (2.30, 3.65), in AMS-1 and by 5.15, CI = (4.09, 6.48), in AMS-2; $F_{2,9} = 133.91$, $P < 0.001$]. Milking phases were longest in ATM, with little difference between AMS-1 and AMS-2 [changes in comparison with ATM: by a factor of 0.76, CI = (0.62, 0.94), in AMS-1 and by 0.75, CI = (0.60, 0.93), in AMS-2; $F_{2,9} = 6.23$, $P = 0.020$]. The milking phase was shorter for cows with higher DIM [by a factor of 9.91/10 DIM, CI = (0.986, 0.996); $F_{1,211} = 11.75$, $P < 0.001$] and longer for those of higher parity [by a factor of 1.05, CI = (1.02, 1.07); $F_{1,211} = 13.30$, $P < 0.001$]. Finally, the length of the exit phase did not differ among the milking systems [changes in comparison with ATM: by a factor of 0.89, CI = (0.55, 1.44), in AMS-1 and by 1.02, CI = (0.63, 1.66), in AMS-2; $F_{2,9} = 0.22$, $P = 0.81$; Figure 2].

There was little difference in the within-system variability in terms of total length of the milking process and the length of the preparation phase. Cows in ATM showed a much greater variability (by a factor of about 7) in the admission phase than in the other 2 systems, whereas the variability was approximately halved in the milking phase (Figure 2). Compared with the AMS-1, variability in the exit time was halved in the AMS-2 and doubled in the ATM.

The 90% quantile of the preparation-phase length was longest for AMS-2 (median of 175 s), followed by AMS-1 (122 s) and ATM (42 s; $H = 9.91$, $P < 0.01$; Table 2). Maximum preparation-phase lengths were greater in the 2 AMS (up to 617 s in AMS-1 and 363 s in AMS-2) than in ATM (up to 144 s; $H = 7.42$, $P = 0.02$; Table 2). There was no difference in the 90% quantiles in terms of exit-phase length (about 25 s in AMS and 30 s in ATM; $H = 0.50$, $P = 0.78$; Table 2). Some extreme lengths

of up to 219 s (AMS-1), 279 s (AMS-2), and 285 s (ATM) were observed.

DISCUSSION

Type of AMS and cow traffic were confounded. Thus, in principle, the effects of these 2 variables cannot be differentiated. Nevertheless, for most aspects, it seems reasonable to assume that 1 of the 2 variables was more likely influential, such that we mostly restrict ourselves to mentioning 1 variable per aspect in the following discussion.

Milk Yield, Milking Frequency, and Intermilking Interval

Milk yield did not differ on the 12 working farms investigated. Although Barnes et al. (1990) asserted that an increase in milking frequency led to an increase in milk yield in conventional systems, others using AMS have not encountered such an effect (Abeni et al., 2005). Not surprisingly, milk yield decreased with DIM and increased with parity, at least in the range of parities in our sample.

Milking frequency was almost stable with increasing DIM in the AMS with selectively guided cow traffic (AMS-2), and the intermilking interval increased much less steeply with DIM than in the AMS with free cow traffic (AMS-1), as could be expected because cows were forced to pass through the milking unit at regular intervals. What was surprising was that cows in the AMS with free cow traffic had a higher milking frequency and shorter intermilking intervals in early lactation than comparable cows in the AMS with selectively guided cow traffic. It would appear that the visits to the milking unit of cows in the AMS with free cow traffic more closely reflected the change in milk yield throughout lactation. Finding a high variation in average milking frequency between cows, Hogeveen et al. (2001) assumed that cow factors (e.g., eagerness to visit the AMS) influenced milking frequency. If we use DIM as a partial explanation of milking frequency, the remaining variation does not appear extreme. The high milking frequency observed in early lactation in AMS-1 may possibly be the result of an increase in capacity caused by less frequent visits by the cows in late lactation and the relatively low number of failed milkings in this AMS model. Thus, the given capacity of the AMS could be used by the cows in a manner that more closely reflected their expected milk yield given DIM, while at the same time keeping the total number of visits to the milking stall per farm on the same level in AMS-1 as in AMS-2. Even though the cow traffic was not implemented in a pure fashion because water provision was restricted to the waiting

area in some of the AMS-1 farms, a distinct pattern of free and selectively guided cow traffic was apparent in our data set. There was no difference in the milking frequency on farms with the 2 cow traffic systems. This was true for cows of second parity or higher observed by Ketelaar-de Lauwere et al. (2000). By contrast, Harms et al. (2002) and Thune et al. (2002) found higher milking frequencies in barns with selectively guided cow traffic than in those with free cow traffic.

Given the management efforts on our study farms (e.g., in fetching cows that had not been milked once or twice daily), a sizeable percentage of milking intervals lasted longer than 12 h. This coincides with the observations made in other studies regarding AMS-1 (17.7%, De Koning and Ouweltjes, 2000; 18%, Hogeveen et al., 2001) and AMS-2 (14%, Melin et al., 2006). Because no data were collected on the frequency of fetching cows that had not been milked for too many hours, we cannot exclude the fact that milking frequency could have been influenced by this activity of the farmers. There were no obvious differences in fetching management between farms with the 2 types of AMS.

Because our set of focal animals had been positively selected, one can expect that milking frequency would be lower and intermilking intervals longer in a larger sample of cows, which would demand greater management effort to reach the same production efficiency.

Teat-Cup Attachment Success

The percentages of successful milkings observed in the current study were similar to other studies carried out with the same AMS models (AMS-1: 95 to 98%, Huschke and Klimetschek, 2000; AMS-2: 90 to 95%, Olofsson et al., 2001). Given a median of 120 milkings/d and farm, we would expect, on average, 4 and 12 failed milkings/d on farms with AMS-1 and AMS-2, respectively. This translates to about 25 and 100 min of unproductive occupation of the milking stall per day in AMS-1 and AMS-2, respectively, which directly reduces the capacity of an AMS by at least 2 and 7%, respectively. Indirectly, capacity may be further reduced if cows return to the AMS sooner after nonmilking visits and failed milkings, as observed on our study farms, supporting data from Ketelaar-de Lauwere et al. (2000). In addition, the unsuccessful attempts involved stimulation of the udder without subsequent milking, causing a temporary reduction in milk yield (Bach et al., 2004). Given the reduction in capacity of AMS and the possible health consequences for dairy cows caused by failed milkings (Stefanowska et al., 2000; Persson Waller et al., 2003), maximizing operational reliability of automatic teat-cup attachment (Harms and Wendl, 2003) is crucial. Our positively selected sample of focal cows may present an

Figure 2. Cumulative lengths of different phases of the milking process of all milkings per cow (tick marks) in 2 types of automatic milking systems (AMS-1, AMS-2) and auto-tandem milking parlors (ATM) on 4 farms each (A to L). Farms within a system and cows within farms are sorted in ascending order by maximum length of a complete milking. The cumulative lengths of the admission phase [0-line to dots (•)], preparation phase [dots (•) to ▲], milking phase (▲ to ▼), and exit phase (vertical line) are indicated. Estimates for the cumulative lengths of the milking phases and their 95% confidence intervals are given for each system by the horizontal lines (A = admission; P = preparation; M = milking; E = exit phase) for cows at the observed median DIM (143) and median parity (2 lactations).

overly optimistic picture, in that more milkings would fail (Table 2) in a broader range of cows and thus reduce the capacity of the AMS by additional visits to the milking unit shortly after failed milkings.

Length of the Milking Phases

The milking process was similar in length on all farms, regardless of their milking systems. This held true de-

spite the average amount of milk, reflected both by the length of the milking phase proper and by a higher milking frequency with the same total milk yield, which was lower per milking in AMS than in ATM. The shorter duration of the milking phase in AMS was offset by the increased duration of the preparation phase as compared with ATM. Svennersten and Samuelsson (1992) suggested that milking time is shortened by feeding the cows during milking in AMS, which causes a faster milk flow, presumably because of the stimulation of oxytocin secretion. Given the differences in milk yield, it was not surprising that the total length of the complete milking process and the length of the milking phase depended on DIM and parity. Preparation phases took about 60 s longer in AMS-2 than in AMS-1, and Hvaale et al. (2002) observed a similar difference (134 s vs. 86 s). This is corroborated by other studies on the AMS systems (AMS-1: 81 to 85 s, Huschke and Klimetschek, 2000; AMS-2: 161 s, Sällvik and Sällvik, 2002). Hagen et al. (2004) and Hopster et al. (2002) measured longer preparation phases in AMS-1, with mean values of 108 and 111 s, respectively.

Admission time was longer in the 2 AMS than in ATM, although this phase accounted for only a small proportion of the complete milking process. This may well be explained because fewer cows are in front of the milking stall at any one time in the AMS compared with the ATM, and there was no potential human pressure on the cows to enter the stall in the AMS as opposed to the ATM. The length of the admission phase was similar to those recorded in prior investigations (mean $\pm$ SE: 18 $\pm$ 0 s, present study; AMS-1: 17 $\pm$ 1.4 s, Hopster et al., 2002; 17 $\pm$ 15 s, Hagen et al., 2004; AMS-2: 22 $\pm$ 1 s, present study; 28 s, Sällvik and Sällvik, 2002). Others have reported much longer admission times in conventional milking systems than observed in this study (ATM: 20 $\pm$ 2 s, present study; 60 $\pm$ 8.9 s, Hopster et al., 2002; herringbone parlor: 77 $\pm$ 54 s, Hagen et al., 2004). Considering that the cow may stand in the milking stall for awhile until the milker has finished some other task in the other milking stalls, it is not surprising that the variability in the admission time was greatest in ATM. Admission time might be critical in cows having trouble adjusting to the AMS or in cows with an udder shape difficult for the AMS, because they may be more hesitant in entering the milking unit. This would increase the time of occupancy of the milking unit and thus reduce the capacity of the AMS.

Exit times were similar in AMS and ATM and comparable to those found in other studies (AMS-1: 12 $\pm$ 0.4 s, Hopster et al., 2002; 43 $\pm$ 65 s, Hagen et al., 2004; AMS-2: 31 s, Sällvik and Sällvik, 2002). If we assume that there is no principal difference in the exit times in the 2 types of AMS, the pressurized-air jet on farms with

AMS-2 did not seem to speed up exit times. According to our data, such an exit drive would not seem to be necessary. Although the flooring in AMS-2 might well be more comfortable for the cows (rubber as opposed to metal), the variability in exit time was smaller in AMS-2 than AMS-1.

CONCLUSIONS

Different technical approaches to automatic milking resulted in differences in teat-cup attachment success, duration of several phases of the milking process, and milking frequency. Free cow traffic in the systems investigated led to milking frequencies reflecting the change in milk production more closely than for selectively guided cow traffic. Although the milking phases were shorter in AMS than in ATM, the preparation phase was longer, with the result that the overall duration of milkings was the same, although milk quantity per milking was lower in AMS. The capacity of an AMS could be further improved by shortening the preparation phase and reducing the proportion of failed milkings.

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