Influence of Air Intake on the Concentration of Free Fatty Acids and Vacuum Fluctuations During Automatic Milking

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ABSTRACT

The main objective of the study was to determine whether the amount of air intake during quarter milking influences the concentration of free fatty acids (FFA) and vacuum fluctuations at the teat end when milking automatically. Air intake in the teat cup was restricted from the normal inlet of 4.5 to 7 L/min to 1.7 and 0 L/min on 2 farms and experiments were carried out as half-udder studies with 40 cows. Blockage of the air inlet reduced FFA from 1.02 to 0.77 mEq/100 g of fat in one herd and from 1.50 to 1.17 mEq/100 g of fat in the other herd. Milk yield per milking was the most significant factor influencing FFA. Air intake accounted for <20% of the variation in FFA concentration. Characteristics of the cow explained the most variation, which could mainly be assigned to the effects of milk yield, fat percentage, fat globule size, and fat globule size distribution. The interval between milkings was not significant when adjusting for milk yields. Blockage of the air inlet caused vacuum fluctuations at the teat end to increase from 15.4 to 21.5 kPa for one model of an automatic milking system (AMS), but from 12.8 to 53.6 kPa for another model. Measurements made with a flow simulator and water revealed that the AMS model and water flow were the most important factors influencing vacuum fluctuations, and that interactions existed between the diameter of the short milk tube and air intake. Free fatty acids in bulk milk from 5,980 herds averaged 0.75 mEq/L of milk for conventional herds and varied from 0.77 to 0.94 mEq/L of milk for the 5 AMS models on the Danish market. Fault detection in 55 herds pointed out that the most frequent faults in conventional herds were air leakages and intake of too much air in the cluster, whereas AMS herds had problems with the cooling and stirring of milk. Correction of the cooling faults caused FFA to decrease by 0.52 mEq/L in the AMS herds. We concluded that air intake during

automatic milking is not the most important factor in reducing FFA, whereas milk yield per milking matters the most. More attention should be paid to the cooling and stirring of milk. Reducing the air intake causes vacuum fluctuations during milking to increase significantly.

Key words: automatic milking, free fatty acid, air intake, vacuum fluctuation

INTRODUCTION

The first commercial automatic milking systems (AMS) were installed in the Netherlands in 1992, and after a moderate start, farmers seriously began investing in AMS in the late 1990s. At the end of 2003, more than 2,200 farms worldwide were milking automatically (de Koning and Rodenburg, 2004). Most of the farmers using AMS give social reasons for investing in them, including increased labor flexibility, improvement of their social life, and health concerns (Mathijs, 2004). There were technical difficulties on the pioneer farms, but the capacity performance of the different AMS models is now generally good and failure rates are low, which allows us to focus on and improve milk quality. The introduction of AMS has been shown to influence milk quality negatively, which has included an increased total bacterial count, increased freezing point of the milk, increased concentration of FFA, and increased bulk milk SCC (Jepsen and Rasmussen, 2000; Klungel et al., 2000; Rasmussen et al., 2002). Many of the problems with elevated bacterial counts, elevated cell counts, and increased freezing point have been solved, but FFA remain a problem for many of the AMS herds, and as such, for the dairy processing industry.

There may be technical as well as physiological reasons for increases in FFA. de Koning et al. (2004) suggested that technical reasons may include inlet of too much air in the teat cups, bubbling of air into the composite milk, and milk pumps running after the milk flow has ceased. Milk yield per milking is lower when milking occurs more frequently. Slaghuis et al. (2004) found a significant increase in FFA with increased milking frequency and especially after 24 h of

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storage, when FFA increased from 0.42 to 0.71 mmol/100 g of fat when going from 2 to 3 daily milkings. These findings are supported by Swedish studies (Wiktorsson et al., 2000; Svennersten-Sjaunja et al., 2002). Moreover, Slaghuis et al. (2004) suggested that the number of failed milkings also may influence FFA. The fat percentage of the milk may be altered by differences in the time interval between milkings and the success rate of milking, and changes in the composition of the feedstuff may cause milk to be more susceptible to lipolysis. Wiking et al. (2003) found that feeding concentrate with a large amount of saturated lipids resulted in an elevated fat percentage and large-sized fat globules, which were very prone to lipolysis. They also found that milk originating from feeding unsaturated fat or from stimulating more *de novo* synthesis caused a reduced fat percentage and fat that was more stable to pumping. In general, the pumping of warm milk with large shear forces resulted in a high FFA content, especially for saturated fat, whereas milk with a reduced fat percentage resisted lipolysis better, especially when pumped at 5°C.

Air admission into the claw during milking is needed whenever the milk must be lifted when using a high-pipeline system. According to International Standard ISO 5707 (ISO, 1996a), the total air admission in a cluster must be between 4 and 12 L/min and leakages must not exceed 2 L/min. Normal air intake during automatic milking is from 4 to 7 L/min per quarter, corresponding to 15 to 28 L/min for 4 teat cups. We suspect that such large air intakes may increase the concentration of FFA because the stability of milk fat globules (MFG) decreases when mixed with air or any gas during pumping or agitation of the milk. Contact between a MFG and an air bubble results in rupture of the MFG membrane, inasmuch as membrane material and part of the core fat will spread over the air–milk plasma interface and will be released into the milk plasma when air bubbles collapse or coalesce (Evers, 2004). However, milking units of an AMS are individual quarter milkers with rather long “short milk tubes,” individual shut-off valves, foremilk separators, and different kinds of milk meters, and the milk normally must be lifted several times before it enters the receiver. Such technical constructions may require different amounts of air for transportation of the milk than conventional milking units. Preliminary studies have shown that vacuum fluctuations at the teat end are larger in AMS than in conventional milking and that blockage of the air inlet may cause vacuum peaks to increase above the milking vacuum (Bjerring and Rasmussen, 2002). The objectives of the present study were first, to assess the influence of air intake during automatic milking on FFA, fat globule size, and vac-

uum fluctuations, and second, to identify factors influencing the FFA content of bulk milk in AMS herds.

MATERIALS AND METHODS

Experiment 1

Air Intake and FFA. Air intake of one randomly selected rear teat cup was reduced during milking of 10 Jersey, 6 Red Danish, and 4 Danish Holstein cows. For 11 cows, air intake was reduced to 1.7 L/min, and during milking of 9 cows, intake was reduced to 0 L/min. The normal air intake of 7 L/min was used on all the other rear teat cups, which served as controls. Cows from the Danish Cattle Research Centre were milked automatically by 2 DeLaval VMS milking units (DeLaval, Vejle, Denmark). Cows were chosen as they entered the milking unit and were only eliminated if they had a dry quarter or their milk yield was too small to obtain a milk sample, which happened for 2 Jersey cows. A T-piece was inserted in the milk tube immediately after the quarter milk flow meter, and a proportion of the milk was drained continuously into a container during milking. A sample of >200 mL was needed for the analysis of acid degree value (ADV) using the Bureau of Dairy Industries (BDI) method (IDF, 1991), for analysis of the milk composition using a MilkoScan 6000 (Foss Electric, Hillerød, Denmark), and for determination of the distribution of fat globule size (Michalski et al., 2001). The samples for analysis using the BDI method were stored at 5°C for 22 h and then pasteurized at 63°C for 0.5 h to inactivate the lipase enzyme. The samples for determination of fat globule size were analyzed within 4 h of milking. The MilkoScan 6000 had been calibrated according to the BDI method and yielded an FFA concentration on the basis of the measured spectrum. The abbreviation FFA is used as the general term for FFA in the following: ADV (Fourier transform infrared spectroscopy; **FT-IR**), for determination of concentrations measured by the MilkoScan 6000; and ADV (BDI), for values measured using the IDF reference method (IDF, 1991). Milk flow meters measured flow, milk yield, and conductivity for each quarter of each cow, and mean values from the previous week were extracted from the database. Each rear teat cup was fitted with a pressure transducer in the mouthpiece chamber, in the short pulse tube, in the short milk tube just beneath the teat cup shell, and in the “short” milk tube about 20 cm after the air inlet.

Experiment 2

Air Intake and FFA. Experiment 1 was repeated during milking of 20 Danish Holstein cows with a Lely

Astronaut model MQC (Lely Denmark, Rødekro, Denmark) on a private farm. The normal air intake of 4.5 L/min was used on one rear teat cup, which served as a control. For 10 of the cows, air intake of the other rear quarter unit was reduced to 0 L/min, and was reduced to 1.7 L/min for the remaining 10 cows. A T-piece was inserted in the milk tube immediately before the conductivity meters and a proportion of the milk was drained continuously into a container during milking. Milk samples were analyzed as described above. Milk samples for the MilkoScan were analyzed in duplicate. Each rear teat cup was fitted with a pressure transducer in the mouthpiece chamber, in the short pulse tube, and in the short milk tube just beneath the teat cup shell (i.e., after the air intake).

Experiment 3

Air Intake, Water Flow, and Vacuum Fluctuations. Vacuum fluctuations were measured during a wet test with one teat cup from Lely Astronaut, one from a DeLaval VMS, and one from SAC Galaxy (SA Christensen, Kolding, Denmark). The AMS models are denoted Models 1, 2, and 3 in the text and tables (randomly chosen). Pressure transducers were mounted at the tip of the ISO-teat (ISO, 1996b), in the short pulse tube, in the short milk tube at the end of the teat cup shell for Model 1, 2 cm and 30 cm after the air inlet of all models, and in the bucket (equal to the vacuum supply). The length of the milk tube was 185 cm and lifting heights were 0, 40, and 90 cm. The diameter of the milk tube was 13 mm for Models 1 and 2, and 11 mm for Model 3. Normal air intakes of the 3 models were: 7.0, 3.6, and 5.4 L/min, respectively. Model 1 normally operates the air intake with an overpressure of about 50 kPa, and without this, the air intake drops to 4.5 L/min. Consequently, an additional air inlet was used to increase the air intake to 6.6 L/min during the wet test of Model 1. In addition to measurements made during normal air intake, air intake was reduced to 0, 0.9, and 2.1 L/min or increased to 7 L/min. Measurements were made during water flows of 0.2, 0.5, 1, and 2 L/min. Pressure transducers sampled at 300 Hz and the minimum response rate was >5,000 kPa/s. For each model, lifting height, water flow, and air intake, sampling was carried out for at least 15 s, and the last 5 s (= 5 pulsations) was used to calculate mean and maximum vacuum in the B-phase, minimum vacuum in the D-phase, and the mean difference between minimum and maximum vacuum during each pulsation cycle. Rate was 60 pulsations/s and the ratio was 60:40. Nominal vacuum was set at 42 kPa.

Experiment 4

Fault Detection in Herds Having Elevated FFA.

Every week from September 1, 2004, to the end of March 2005, bulk milk samples of all 5,980 Arla Foods (Viby, Denmark) herds in Denmark were analyzed for ADV (FT-IR) using the calibrated MilkoScan 6000. The slope and intercept were adjusted every week using 10 to 15 different bulk milk samples that also were analyzed using the reference ADV (BDI) method. The data set consisted of milk samples from herds with both conventional milking and automatic milking. Five AMS models are on the Danish market, and the model and starting dates of all AMS herds were known from the Danish self-monitoring program (Rasmussen et al., 2002) but are denoted as Models 1 to 5 in the results.

Every week from October to the end of December 2004, the 2 AMS and 3 conventionally milked herds having the greatest ADV (FT-IR) means of that week were visited by a milk quality inspector. The ADV (FT-IR) means were a sum of the last 4 running ADV (FT-IR) values weighted by 0.5, 0.2, 0.2, and 0.1 [i.e., giving the latest ADV (FT-IR) value the weight 50%]. A total of 24 AMS herds and 31 herds with a conventional high-pipeline milking system were appointed, but none with a low-line parlor milking system. During the visit by the milk quality inspector, milking systems were inspected for air leakages, installation faults, leveling, malfunctioning of the milk pump, and faults in the cooling system. A general subjective score was given for maintenance, ranging from 1 for a perfect system to 5 for a system needing heavy maintenance. Air intake per teat cup (AMS) and cluster (conventional milking) was measured and a score was given for air intake at attachment. The pump line diameter was measured, as was the rise and fall of the pump line. Only 5 herds used systems for precooling milk, and 8 herds had ice-bank cooling. The inspector noted whether the bulk tank was filled from the top or the bottom. A list of the top 3 priorities for things that needed correction was given to each herd owner after the visit. About 4 to 8 wk after the visit, dairy farmers of the visited herds were contacted by telephone to determine whether each recommendation was carried out. Farms were classified according to whether recommendations 1) were followed by correcting all faults, 2) partly followed by correcting at least one fault, or 3) not followed, when none was corrected. It was the responsibility of the dairy farmer to accept or not accept recommendations.

Statistical Methods

A mixed-model procedure (PROC MIXED; SAS Inst. Inc., Cary, NC) was used to test the concentration of

FFA of the 2 methods (BDI, FT-IR). Equation [1] was used for Experiment 1:

$$Y_{ijk} = \mu + \text{air}_i + \text{breed}_j + \text{air} \times \text{breed}_{ij} + \varepsilon_{ijk}, \quad [1]$$

where Y_{ijk} is FFA, μ is the overall mean, air_i is the effect of air intake ($i = 0, 1.7, 7.0$ L/min), breed_j is the effect of breed ($j = \text{Danish Jersey, Red Danish, Danish Holstein}$), $\text{air} \times \text{breed}_{ij}$ is the interaction between air intake and breed, and ε_{ijk} is the residual error.

Cow was included as a random effect and was used to test differences among breeds. The effect of air intake and breed on quarter milk yield, fat percentage, fat globule size, peak flow, and conductivity was also tested using Equation [1]. In addition, the breed of Equation [1] was replaced by milk yield, fat percentage, and fat globule size. Relative milk yield, milk flow, and conductivity per quarter were adjusted for the means of the previous week and tested in Equation [1]. Results from Experiment 2 also were tested as for Experiment 1, except that breed was not included in the model, and as for analysis of milk composition and FFA, cow $\times$ quarter was included as the repeated subject.

Vacuum fluctuations during flow simulation using the ISO-udder (ISO, 1996b) were analyzed by using a GLM (PROC GLM; SAS Inst. Inc.):

$$Y_{ijkl} = \mu + \text{model}_i + \text{height}_j + \text{water}_k + \text{air}_l + M \times H_{ij} + M \times W_{ik} + M \times A_{il} + H \times W_{jk} + H \times A_{jl} + W \times A_{kl} + \varepsilon_{ijkl}, \quad [2]$$

where Y_{ijkl} is vacuum fluctuations at the ISO-teat (ISO, 1996a) end before, after, or 30 cm after the air intake; μ is the overall mean; model_i is the effect of the model ($i = 1, 2, 3$; $i = 0, 1.7, 7.0$ L/min); height_j is the effect of height ($j = 0, 40, 90$ cm); water_k is the effect of the water flow ($k = 0.2, 0.5, 1.0, 2.0$ L/min); air_l is the effect of air intake ($l = 0, 0.9, 2.1, 4$ to $5, 7$ L/min; all second-term interactions among the 3 variables); and ε_{ijkl} is the residual error.

The ADV (FT-IR) values were transformed using the cubic root to obtain a normal distribution of data before analysis in Equations [3] to [5]. Data were transformed back before presentation. The influence of the type of milking system on ADV (FT-IR) of bulk milk was tested by a mixed model:

$$Y_{ijk} = \mu + \text{model}_i + \varepsilon_{ijk}, \quad [3]$$

where Y_{ijk} is the ADV (FT-IR) of bulk milk, μ is the overall mean, model_i is the effect of the model ($i = \text{conventional milking machine, or each of 5 AMS}$), and ε_{ijk} is the residual error. The effect of date ($j = 1, \dots,$

89) was included as a repeated variable with herd ($k = 1, \dots, 5,980$) as the random subject.

The effect of faults found and corrected after a visit by a milk quality inspector in herds having elevated ADV (FT-IR) was tested within the milking system (conventional or AMS) by a mixed model:

$$Y_{ijklmnop} = \mu + \text{air}_i + \text{leakage}_j + \text{pump}_k + \text{cooling}_l + \text{stirring}_m + \text{others}_n + \text{days}_o + \varepsilon_{ijklmnop}, \quad [4]$$

where $Y_{ijklmnop}$ is the ADV (FT-IR) in the period either 60 d before or after correction of faults, μ is the overall mean, days_o is the days before or after correction, and ε_{ijkl} is the residual error.

When analyzing ADV (FT-IR) values before the visit by the milk quality inspector, the variables included were air intake, leakage, pump, cooling, stirring, and others, with others representing faults vs. no faults detected at these respective places at the visit. After the visit, these variables referred to faults having been corrected or not. The effect of date ($j = 1, \dots, 89$) was included as a repeated variable with herd ($k = 1, \dots, 55$) as the random subject. The overall effect of corrections for faults was analyzed with the following mixed model:

$$Y_{ijklm} = \mu + \text{system}_i + \text{period}_j + \text{days}(\text{period})_{jk} + \text{system} \times \text{period} \times \text{correction}_{ijl} + \varepsilon_{ijklm}, \quad [5]$$

where Y_{ijklm} is ADV (FT-IR), μ is the overall mean, system_i is the effect of the milking system (conventional or AMS), period_j is the effect of the period before or after the visit, $\text{days}(\text{period})_{jk}$ is the days within the period, $\text{system} \times \text{period} \times \text{correction}_{ijl}$ is the effect of the correction of faults (yes, partly, no) within the system and period, and ε_{ijklm} is the residual error. Date and herd were included as for Equation [4].

RESULTS AND DISCUSSION

FFA

Values for ADV (BDI) tended ($P < 0.10$) to decrease from 1.02 mEq/100 g of fat for the normal air inlet to 0.77 mEq/100 g of fat for a blocked air inlet. Values for ADV (FT-IR) did not change when decreasing the air inlet from 7 to 1.7 L/min, but tended to decrease from 0.85 to 0.70 mEq/L when the air inlet was totally closed. Jersey cows had the greatest concentration of FFA, but differences among breeds were not significant (Table 1). Quarter milk yield ($P < 0.05$) was the lowest and fat percentage ($P < 0.01$) and fat globule size ($P < 0.001$) were the greatest in Jersey cows, but these variables were not significantly influenced by

Table 1. Influence of air intake and breed [Jersey, Red Danish (RD), Danish Holstein (DH)] on the concentration of FFA (measured by 2 different methods), fat percentage and globule size, milk yield and flow, and conductivity when milking automatically (Experiment 1)

Item	Air intake, L/min			SEM	P	Breed			
	0	1.7	7.0			Jersey	RD	DH	P
No. of samples/cow	9	11	20			10	6	4	
ADV (BDI), ¹ mEq/100 g of fat	0.77	0.90	1.02	0.16	<0.1	1.16	0.72	0.80	NS
ADV (FT-IR), ² mEq/L of milk	0.70	0.85	0.85	0.11	NS	0.99	0.72	0.69	NS
Quarter milk yield, kg	3.74	3.23	3.05	0.42	NS	2.22 ^a	3.63 ^{ab}	4.16 ^b	<0.05
Fat, %	4.80	4.89	4.83	0.31	NS	6.06 ^b	4.56 ^a	3.89 ^a	<0.01
Globule size, μ m	4.88	4.89	4.87	0.14	NS	5.66 ^b	4.37 ^a	4.61 ^a	<0.001
Peak milk flow, kg/min	1.54 ^b	1.44 ^{ab}	1.20 ^a	0.11	<0.05	1.12 ^a	1.48 ^b	1.59 ^b	<0.05
Conductivity, mS/cm	5.34 ^b	5.17 ^b	4.61 ^a	0.15	<0.001	4.14 ^a	5.36 ^b	5.62 ^b	<0.001

^{a,b}Means within a row and category (air intake vs. breed) bearing different superscript letters differ ($P < 0.05$).

¹Concentrations of FFA determined by the Bureau of Dairy Industries (BDI) method (IDF, 1991). ADV = acid degree value.

²Concentrations of FFA determined by the MilkoScan 6000 (Foss Electric, Hillerød, Denmark). FT-IR = Fourier transform infrared spectroscopy.

air inlet. However, air intake and breed influenced the peak flow rate ($P < 0.05$) and conductivity ($P < 0.001$). The influence of air intake on these 2 measures was solely because of measurement error when the air intake was restricted, which resulted in excessive flow rates and elevated conductivity values. After adjustment for milk yield, peak flow, and conductivity of the quarters assessed during the previous week, there seemed to be an increase in these values of 14, 38, and 27%, respectively.

Milk yield was the best variable to explain differences in ADV (BDI) between samples (Figure 1), whereas fat percentage and fat globule size contained no additional explanation for differences in milk yields. Values for ADV (BDI) decreased by 0.16 mEq/100 g of fat per extra liter of milk. Air intake accounted for <20% of the variation in ADV (BDI) and ADV (FT-

IR), cow number for about 75%, and the remaining 5% was residual error. Knowledge of milk yield, fat percentage, average fat globule size, and average fat globule distribution could partly substitute for cow in the model, and explained 59% of the variation in ADV (FT-IR) and 28% of the variation in ADV (BDI). Milking interval since last milking was not significant in these models ($P > 0.50$) when milk yield was taken into account. This shows the importance of setting a lower limit of expected milk yield per milking so as not to increase FFA.

For Experiment 2, reduction in the air intake significantly reduced ADV (FT-IR) from about 1.2 to about 0.8 mEq/L of milk and reduced ADV (BDI) from about 1.5 to about 1.2 mEq/100 g of fat (Table 2). The fat percentage was lowest in the rear quarters milked with a closed air intake, but because the fat percentage was highest in the medium air intake, we suspect that this significant effect was due to true but random differences between measured quarters. No difference was detected in fat globule size among the 3 different air intakes. Total milk yield of the cow tended ($P < 0.10$) to influence ADV (BDI) and ADV (FT-IR) values, which decreased by 0.11 mEq/100 g of fat, and decreased ($P < 0.001$) by 0.16 mEq/L per extra liter of milk, respectively. Milk yield explained about 50% and air intake 30% of the model error for ADV (FT-IR), and the remaining 20% was explained by fat percentage, machine-on time, and fat globule size. Fat percentage did not influence ADV (BDI) and ADV (FT-IR) significantly, whereas ADV (FT-IR) increased ($P < 0.05$) with increasing fat globule size. These changes agree with another report (Wiking et al., 2003) in which milk with large MFG had an inherently greater ADV (FT-IR). An increase in machine-on time in-

Figure 1. The acid degree value [mmol/100 g of fat, BDI method (IDF, 1991)] depends on milk yield per quarter. Results are shown for air intakes of 0 ($\square$), 1.7 ($\times$), and 7 L/min ($\blacktriangle$; Experiment 1).

Table 2. Influence of air intake on the concentration of FFA (measured by 2 different methods) and globule size during automatic milking (Experiment 2)

Item	Air intake, L/min			SEM	P
	0	1.7	4.5		
No. of samples	10	10	20		
ADV (BDI), ¹ mEq/100 g of fat	1.17	1.18	1.50	0.20	NS
ADV (FT-IR), ² mEq/L of milk	0.78 ^a	1.06 ^b	1.19 ^b	0.12	<0.001
Fat, %	3.42 ^a	3.78 ^b	3.73 ^b	0.13	<0.01
Globule size, μ m	4.36	4.58	4.36	0.14	NS
Teat cup on-time, min	3.86	4.31	4.04	0.42	NS

^{a,b}Means within row bearing different superscript letters differ ($P < 0.05$).

¹Concentrations of FFA determined by the Bureau of Dairy Industries (BDI) method (IDF, 1991). ADV = acid degree value.

²Concentrations of FFA determined by the MilkoScan 6000 (Foss Electric, Hillerød, Denmark). FT-IR = Fourier transform infrared spectroscopy.

creased ($P < 0.001$) ADV (FT-IR), with 0.23 mEq/L of milk per extra minute of milking. The correlation between ADV (BDI) and ADV (FT-IR) values from Experiments 1 and 2 analyzed together was 0.77. The relationship was linear, but ADV (FT-IR) values were lower ($P < 0.001$) than ADV (BDI) values at the upper end of the scale ($\text{FT-IR} = 0.34 + 0.49 \times \text{BDI}$). Although concentrations of ADV (FT-IR) and ADV (BDI) did not have quite the same readings, the trends and effects of treatments could be evaluated with confidence for both analyses.

The FFA content of raw milk is known to be greater in more frequently milked cows (Wiktorsson et al., 2000; Slaghuis et al., 2004; Wiking et al., 2005). That may be explained by a weakness in the MFG, because greater milk concentrations of FFA from cows milked more frequently are observed only after storage of the raw milk and the average diameter of MFG is larger in milk from udder halves milked more frequently (Wiking et al., 2006). However, the average milking frequency in AMS is only between 2.4 and 2.6 daily (Hogeveen et al., 2001; Petterson and Wiktorsson, 2004); therefore, it is very likely that mechanical factors also have an impact on the increased content of FFA in milk from AMS. This is in agreement with our results in which a reduction in air intake, and as such, in the mechanical treatment of the fat globules, reduced the FFA content. Likewise, the more milk per milking or per liter of air, the smaller the FFA content. Mechanical treatment of the fat globules during milking is important for the FFA content, but this accounted for only about 20% of the variation, compared with the 59 to 75% explained by differences between cows, such as milk yield, fat percentage, and fat globule size. Because milk yield was the most significant factor, restrictions on renewed milking by the AMS should be enforced when a minimum amount of milk yield is expected. In agreement with the present study,

Needs et al. (1986) reported that using a claw piece requiring a large air bleed (14 L air/min), instead of a conventional claw, increased the FFA concentration by 21%. O'Brien et al. (1998) found similar results.

Vacuum Fluctuations During Milking

Vacuum fluctuations at the teat end during Experiment 1 averaged, for the whole milking, 21.5, 16.9, and 15.4 kPa for air intakes of 0, 1.7, and 7.0 L/min, respectively (treatment effect; $P < 0.001$). Vacuum fluctuations were largest during the peak flow phase when the air intake was restricted (Figure 2), and only minor differences existed during the limited flow periods. The interaction between air intake and phase of milking was not significant ($P = 0.20$). Vacuum fluctuations measured downstream of the air intakes were of similar magnitude closer to the teat end. Mean vacuum at the teat end was 39.4 kPa during overmilking and 37.2 kPa during the peak flow, and milking without air intake increased ($P < 0.001$) the mean vacuum of 1.2 kPa in comparison with the normal air intake. Mean vacuum values during the detachment phase were 20.8, 18.2, and 15.5 kPa for air intakes of 0, 1.7, and 7.0 L/min, respectively (treatment effect; $P < 0.001$), which shows that it takes a longer time to equalize pressure in the liner with a closed air intake. Reverse-pressure gradients in the mouthpiece chamber occurred in all phases of milking but lasted <2% of the time of the first 4 phases, compared with 27% of the detachment phase. Reverse-pressure gradients during this phase may cause bacteria to penetrate the teat canal (Rasmussen et al., 1994), but the duration of mouthpiece chamber reverse-pressure gradients was independent of air intake.

A significant interaction was detected between milking phase and air intake for the AMS model used in Experiment 2. Vacuum fluctuations during peak flow

Figure 2. Vacuum fluctuations in the short milk tube just beneath the shell during automatic milking with different air intakes (SEM = 1 kPa; Experiment 1).

averaged 53.6 kPa with the air vent closed, compared with 16.6 and 12.8 kPa for 1.7 and 4.0 L/min, respectively (treatment effect; $P < 0.001$). Reducing the air intake from 4 to 1.7 L/min caused increases in vacuum fluctuations similar to those in Experiment 1, but total blockage of the air vent caused peaks of vacuum to increase ($P < 0.001$) above the milking vacuum, with peaks around 70 kPa during the period with high milk flow rates. Because of the design of the teat cup and cleaning between milkings of each cow, however, it is uncommon to find blocked air vents with this system. The average vacuum was greater and the decrease in vacuum was more abrupt during the detachment phase when the air intake was reduced.

Vacuum Fluctuations During Simulated Flow

The AMS model and water flow were the most significant variables and explained 74% of the variation in vacuum fluctuations at the teat end. Remaining variables and their interactions explained a further 22%, and the residual error accounted for 4%. Vacuum fluctuations increased ($P < 0.001$) with increasing water flow, especially in the AMS model having the

Table 3. Vacuum fluctuations¹ (kPa) at the teat end during simulated water flow based on 3 different models of automatic milking systems (Experiment 3)

AMS model	No.	Water flow, L/min			
		0.2	0.5	1.0	2.0
1	60	11.0 ^a	12.5 ^{ab}	20.5 ^{de}	28.4 ^h
2	60	12.5 ^{ab}	13.8 ^b	16.8 ^c	24.1 ^f
3	60	18.0 ^{cd}	23.1 ^{ef}	31.4 ^g	46.4 ⁱ

^{a-i}Means bearing different superscript letters differ ($P < 0.01$).

¹Vacuum fluctuations are the mean of 5 pulsation cycles and measured as the maximum minus the minimum within each cycle (SEM = 0.7).

Table 4. Vacuum fluctuations¹ (kPa) after air intake during simulated water flow based on 3 different models of automatic milking systems (Experiment 3)

AMS model	No.	Water flow, L/min			
		0.2	0.5	1.0	2.0
1	60	11.0 ^a	11.7 ^a	16.4 ^b	20.5 ^{cd}
2	60	15.6 ^b	16.4 ^b	20.2 ^{cd}	23.3 ^d
3	60	18.7 ^{bc}	21.8 ^{cd}	30.7 ^e	35.5 ^f

^{a-f}Means within a model bearing different superscript letters differ ($P < 0.01$).

¹Vacuum fluctuations are the mean of 5 pulsation cycles and measured as the maximum minus the minimum within each cycle (SEM = 0.9).

smaller diameter milk tube (Table 3). Vacuum fluctuations were generally slightly smaller when measured after the air intake (Table 4), which is the place where transducers are normally mounted during the milking of cows.

In general, increasing the water flow from 0.2 to 2.0 L/min increased ($P < 0.001$) vacuum fluctuations at the teat end by about 20 kPa; adding a lifting height increased ($P < 0.001$) fluctuations by about 5 kPa at small flow rates (Figure 3); and blocking the air vent increased ($P < 0.001$) fluctuations by about 10 kPa. The largest ($P < 0.001$) fluctuations were detected in the AMS model with 11-mm diameter milk tubes. Only small interactions ($P < 0.05$) between the AMS model and height were present, whereas an interaction ($P < 0.001$) was detected between the model and air intake. Blockage of the air intake had less influence on vacuum fluctuations in Model 1 but had a larger effect on the other 2 models (Table 5). In conclusion, blockage of the air vent had a major influence on vacuum fluctuations. At present, we do not know whether large vac-

Figure 3. Vacuum fluctuations (in kPa) at the ISO-teat end (ISO, 1996b) during water flow from 0.2 to 2.0 L/min depending on lifting heights of 0, 40, and 90 cm (Experiment 3). ISO = International Organization for Standardization.

Table 5. Vacuum fluctuations¹ (kPa) at the ISO-teat end (ISO, 1996b) during simulated flow with water and air intake from 0 to 7 L/min based on 3 different models of automatic milking systems (Experiment 3)

AMS model	No.	Airflow, L/min				
		0	1	2	4	7
1	60	21.1 ^{def}	18.8 ^{cde}	17.8 ^c	16.9 ^{bc}	16.0 ^{abc}
2	60	20.8 ^{def}	18.3 ^{cd}	16.8 ^{bc}	14.6 ^{ab}	13.5 ^a
3	60	41.0 ^h	32.4 ^g	30.2 ^g	23.5 ^f	21.6 ^{ef}

^{a-g}Means bearing different superscript letters differ ($P < 0.01$).

¹Vacuum fluctuations are mean of 5 pulsation cycles and measured as maximum minus minimum within each cycle (SEM = 0.8). ISO = International Organization for Standardization.

uum fluctuations affect the udder health of cows milked with quarter milkers.

Fault Detection in Herds Having High FFA

Mean ADV (FT-IR) values per week of all sampled herds remained between 0.7 and 0.8 mEq/L of milk, except for the last 6 to 8 wk, when the weekly mean increased to about 0.9 mEq/L of milk. We suspected that this was due to a calibration error, and consequently, we corrected all values within a week with respect to the overall mean for conventional herds of 0.75 mEq/L of milk. We did not have information on the milking systems in all the conventionally milked herds and consequently, could not divide this group into herds having high- and low-pipeline milking systems. However, values for ADV (FT-IR) in milk from AMS herds were generally greater than those from the conventional herds, with some differences occurring among models (Table 6). The AMS Models 3 and 5 use smaller diameter “short” milk tubes (about 10 to 11 mm) than the remaining AMS models (diameters about 13 mm), but apart from that, we have no plausi-

ble explanation why differences occurred between milking systems.

In the 55 herds that were visited by a milk quality inspector, ADV (FT-IR) values dropped, on average, from 1.82 before to 1.32 mEq/L of milk after the visit. Their concentration increased over some time (about 2 mo) before the visit and then decreased during the following months. The decrease was largest for conventional herds but depended on their starting value and on whether they followed the recommended fault corrections (Table 7). No difference in ADV (FT-IR) values occurred after having corrected for herds with automatic milking. Values for ADV (FT-IR) in herds that followed the advice to correct faults related to high ADV (FT-IR) decreased more than in herds not correcting these faults, but the difference was not significant. The most frequent faults in conventional herds were leakage (71% of the herds) and intake of too much air in the cluster (61%), whereas pumping and stirring faults occurred on 29% of the farms. The main faults for AMS concerned stirring (79%), the pumping of milk (67%), and the cooling of milk (58%). Air leakage was found in only 4% of the AMS. Conventionally milked herds having air leakage had, on average, an ADV (FT-IR) value that was 0.16 mEq/L greater ($P < 0.05$) than that in herds with other faults but no air leakage. None of the other faults seemed worse than others. None of the factors on AMS farms was singled out as the most important before corrections were made. When comparisons could be made within a farm, correction for cooling faults of the AMS (e.g., freezing of the milk) had the largest effect on ADV (FT-IR) values, decreasing ($P < 0.05$) them by 0.52 mEq/L of milk compared with only 0.04 mEq/L of milk for those not correcting the problem. Correction of the remaining factors, such as stirring of the milk in the bulk tank, pumping of the milk, and air intake in the teat cup,

Table 6. Mean concentration of FFA¹ in milk from conventional herds and herds with different types of automatic milking systems from September to December 2004 (Experiment 4)

Milking system	No. of herds	No. of samples	Mean ADV, mEq/L of milk	Herd means ²		Individual samples ²	
				Min 10%	Max 90%	Min 1%	Max 99%
Conventional	5,614	157,847	0.75 ^a	0.48	1.04	0.22	1.58
AMS model							
1	90	2,618	0.92 ^b	0.72	1.10	0.50	1.73
2	207	5,958	0.89 ^b	0.68	1.04	0.42	1.64
3	25	722	0.82 ^{a,b}	0.68	1.04	0.40	1.39
4	7	195	0.94 ^b	0.79	1.12	0.55	1.78
5	37	1,081	0.77 ^a	0.61	1.10	0.31	1.41

^{a,b}Means bearing different superscript letters differ ($P < 0.05$).

¹Acid degree value (ADV) determined by Fourier transform infrared spectroscopy (FT-IR). Concentrations of FFA determined by the MilkoScan 6000 (Foss Electric, Hillerød, Denmark).

²Minimum and maximum values of the confidence interval are given for individual measurements and for averages per herd.

Table 7. Effect of advising herds with conventional high-pipeline milking and automatic milking systems on FFA concentrations¹ in herd milk (Experiment 4)

Item	Conventional milking, mEq/L of milk				Automatic milking, mEq/L of milk			
	No.	Before	After	Diff.	No.	Before	After	Diff.
Recommendations followed	15	1.89 ^a	1.24 ^a	0.65	4	1.75 ^b	1.23	0.52
Recommendations partly followed	10	1.96 ^a	1.38 ^b	0.58	11	1.66 ^{ab}	1.22	0.44
Recommendations not followed	6	2.15 ^b	1.66 ^c	0.49	9	1.57 ^a	1.24	0.33

^{a-c}Means within column bearing different superscript letters differ ($P < 0.05$).

¹Concentrations of FFA determined by the MilkoScan 6000 (Foss Electric, Hillerød, Denmark).

had only minor influences on the drop in ADV (FT-IR) values of AMS herds. Conventional herds that corrected stirring of the milk in the bulk tank tended ($P < 0.10$) to decrease ADV (FT-IR) values, on average, by 0.55 mEq/L of milk, compared with 0.23 mEq/L of milk for those not correcting the problem. Typical stirring faults included the rudder blade not being covered by milk and the rotation speed being too high. It was surprising that none of the other factors was a significant source of variation in conventional herds, but obviously, the cooling and stirring of bulk milk are generally very important factors influencing the FFA content. In this respect, Wiking et al. (2005) concluded that milk should be cooled to 4°C before pumping to avoid an increase in FFA.

General Discussion

High ADV in milk from herds having AMS is a serious problem that must be addressed and resolved. Our “old” knowledge for solving problems in conventionally milked herds has suggested that we focus on air intake in the milking unit. Air intake during milking with an AMS is about 3 to 4 times greater than in conventional clusters. However, this factor did not have the largest influence on FFA at the cow or herd level. The milk yield at each individual milking influences the FFA concentration more than does air intake. Cows producing small milk yields per milking will have greater FFA concentrations, and planning of automatic milkings should consequently ensure that expected milk yields are not too small. Milk from late-lactation cows seems to be more susceptible to lipolysis than that of early-lactation cows (Klei et al., 1997). For some herds in which the feeding regimen makes milk more unstable (Wiking et al., 2005), dairy farmers may be forced to accept a milking frequency of less than 2 milkings per day for the low-yielding cows. We did not investigate this in our study, but a large frequency of unsuccessful incomplete milkings of some of the quarters that have a high proportion of air to milk may increase the FFA concentration. Technical adjustments to the

AMS may resolve these problems (Slaghuis et al., 2004).

We expected air intake into the milking unit and leakages to have a large influence on FFA, and this could have been the case on individual farms. However, fault detection in problem herds revealed that more attention should be paid to the cooling and stirring of milk. Herds having AMS take longer to fill the bulk tank. It is important that milk does not freeze because of too high a cooling capacity and that it is not stirred until the milk fully covers the rudder blade. It is preferable to cool the milk before pumping (Wiking et al., 2005).

Air intake in the milking unit has a minor influence on FFA compared with other factors, but has a major effect on vacuum fluctuations when the air intake is restricted. Design changes within the flow stream from the teat end to the bulk tank may reduce the FFA concentration of cows milked automatically, but care must be taken that a normal milking can be accomplished.

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