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Milkline vacuum stability in milking machine installations

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SUMMARY. Transient vacuum drops in the milkline during one ordinary milking were recorded as a measure of vacuum stability in milking installations on 184 Norwegian dairy farms in the summer of 1997. An association between the frequency of vacuum drops and technical data including milkline diameter, length and slope, number of milking units and effective reserve was demonstrated. The direct connection between the transient vacuum drop and its cause could be established for most drops during milking observations. A high frequency of transient vacuum drops in the milkline was associated with a high level of mastitis and a high new infection rate as inferred from changes in somatic cell counts for individual cows. The frequency of vacuum drops during one milking is only a rough indication of the long-term vacuum stability in a specific installation, and must be interpreted with care. The dimensions and slope of the milkline and the effective reserve probably give as good information about the installation's ability to maintain a stable vacuum.

KEYWORDS: Milking machine, vacuum stability, vacuum fluctuations, milkline, effective reserve, mastitis.

Since Nyhan (1968) hypothesized that irregular vacuum fluctuations at the teat adversely affect udder health, milking machine engineers have put much effort into standards and recommendations to promote vacuum stability in milking machine installations. The hypothesis tested here was that vacuum instability in the milkline reflects the sum of deficiencies in the vacuum pump, the regulator, sizes of the pipelines and details of the installation's design. Monitoring the vacuum in a milkline during milking should therefore tell us whether the installation works properly under the existing conditions, and monitoring during ordinary milking should tell us whether the plant functions as intended in a given herd with given operator(s).

Equipment is now available to monitor vacuum over a complete milking, and some advisors have started to use it. A skilled advisor can extract a lot of information from a vacuum curve, but there is a lack of knowledge on how to systematically extract one, or a few parameters that can be comprehensive descriptors of the vacuum conditions in the milkline. Research in this field will not only contribute to understanding the vacuum conditions in the milking installation, but will also be of practical help for advisors doing milking-time tests.

The aim of the present investigation was to study vacuum conditions in the milkline and the influence of technical specifications; to search for one or more

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parameters to give a comprehensive description of the vacuum stability; and to document the properties of this parameter(s) in its association with udder health.

MATERIALS AND METHODS

Field measurements were made in nine districts chosen to represent the variation in the structure of Norwegian dairy husbandry. Within each district, all dairy farms or a random sample of the farms were chosen. In all, 184 herds were visited between June and August 1997. The herds were all of the Norwegian Red Cattle breed with a herd size of 4·1–39·9 (average, 17·0) cow-years. The term, 'cow-years', describes the average number of lactating cows, including dry ones, in the relevant year.

Repeated measurements on five consecutive milkings on two farms were made in summer 1999.

Vacuum Drop In Milkline (VADIM); minimum-vacuum logging unit

A series of vacuum loggers was designed for the investigation. A Keller PA 10 pressure transmitter (Keller AG für Druckmesstechnik, Reinach, Switzerland) and a Tinytag miniature voltage data logger (Gemini Data Loggers Ltd, Chichester, U.K.) were combined with a minimum voltage filter in an 80 mm × 120 mm × 55 mm box (Fig. 1). The box had a vacuum connector for Ø 14–16 mm milk tube, and an electric connector for RS 232 communication with a PC. Standard software for the Tinytag data logger was used for controlling the logger and for presentation of vacuum curves. The logger unit, which had the capacity for 7800 readings at a minimum interval of 1 s, was run with a logging interval of 2 s. It was run in two modes: in online mode, the vacuum curve was displayed on the computer screen in real time; in offline mode, data were stored internally and read out to the computer when the measurements were complete. When tested as described by Reinemann *et al.* (1996), the response rate of the vacuum transmitter combined with the filter was 350 Hz. The logging unit worked in steps of 0·4 kPa. This constitutes the major part of the measuring error when repeatability is considered. Values for vacuum level were neither calibrated nor used in the study. An example of vacuum curves obtained with a logging interval of 2 s is shown in Fig. 2. Each point represents the minimum vacuum in the 2 s preceding the measurement. During normal operation, the vacuum in the milkline will be fairly constant, and the vacuum will fluctuate within only some tenths of a kPa for most of the time. If the vacuum drops, owing to a change in flow, the minimum value will be recorded regardless of the duration of the drop.

The logging unit was attached to a milk cock as far from the receiver as possible, which was thought to be the position at which vacuum fluctuated the most.

Variables for statistical analysis and guidelines for recommendations to the farmer were extracted from the minimum vacuum curve. The numbers of events when the vacuum suddenly dropped more than 2, 5 and 8 kPa, respectively, below the constant vacuum level were used as variables. The constant level was determined as a running mean of recorded minimum vacuums in periods with no drops.

Dimensions and performance of the milking installation

The diameter and length of the milkline were measured. In addition, the slope of the milkline was checked with an ASTROWATER (AST Måleinstrumenter AS, Norway) water hose levelling apparatus. A profile of the milkline was drawn, and the lowest average inclination of a 10-m section was defined as the slope of the milkline. The system working vacuum was measured on the milkline with a Nuova Fima

Fig. 1. VADIM logging unit attached to a milk cock.

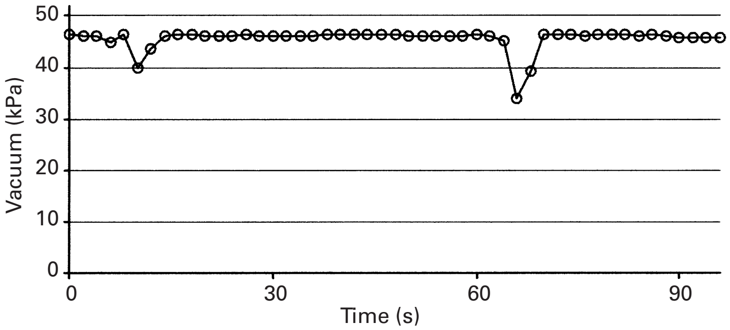

Fig. 2. Example of a vacuum graph obtained with VADIM. Distinct short-term drops in the curve reflect extraordinary air inlet in the installation, e.g. during teatcup attachment.

vacuum gauge (Nuova Fima SpA, Italy) checked against a mercury manometer before the start of the investigation. The effective reserve was measured near the receiver, according to ISO standards (ISO, 1996*b*) with an AFM 3000 airflow meter (Alfa Laval Agri AB, Stockholm, Sweden).

Monitoring of milking

To detect the various events that lead to vacuum drops, the field technician was present during milking on ~ 25 % of the checked farms, and observed vacuum curves and the milking routine. Technicians were told to check for liner slips and cluster fall-offs, to note the milker's handling of the milking unit and to look for events that could allow extra air to enter the milkline. This might be air leakage on cluster attachment and detachment, deliberately letting air into the cluster after detachment in order to empty the unit (air injection), or air leakage when connecting or disconnecting the unit from the pipelines. The events were time-stamped for synchronization with the vacuum curves.

Table 1. *Variables used for statistical analysis*

Symbol	Definition	Average value	SD
MLDIAM	Inner diameter of milkline, mm	35·8	3·9
MLLEN	Length of milkline, m	49	14
MLSLOPE	Minimum average slope of any 10 m section of the milkline, mm/m	2·0	1·6
UNITS	Number of milking units used	3·1	0·8
ER	Effective reserve of milking installation, l/min	263	114
VBMT	Vacuum bulk milk tank used (No = 0, Yes = 1)	0·30	
NDROP2	Number of vacuum drops ⩾ 2 kPa per milking	12·2	9·1
NDROP5	Number of vacuum drops ⩾ 5 kPa per milking	4·5	4·8
NDROP8	Number of vacuum drops ⩾ 8 kPa per milking	2·1	2·6
REGTIME	Duration of period with vacuum recording, hours	0·67	0·26
PDROP2	Predicted frequency of vacuum drops ⩾ 2/h*	18·7	6·6
PDROP5	Predicted frequency of vacuum drops ⩾ 5/h*	6·8	3·2
PDROP8	Predicted frequency of vacuum drops ⩾ 8/h*	3·2	1·6
NMAST	Number of cases of clinical mastitis in the herd	8·3	5·1
NEWINF	Number of cases of new infections in the herd	10·7	4·2
LESION	Incidence of treated teat lesions in the herd, %	4·1	5·8
HSIZE	Number of lactating cows, cow-years	17·9	6·0
COUNTY	County where the farm is located		

* See text for explanations of these variables.

Udder health

Data on udder health were taken from the Norwegian Dairy Herd Recording System, which also contains the health card records (Østerås & Spanne, 1998). The number of cases treated by the veterinary surgeon for acute clinical mastitis was used as a herd variable for mastitis, and the number of cases treated for teat lesions as a variable for teat lesions. Another measure of udder health was the new infection rate. This measure was based on bimonthly or monthly somatic cell count (SCC) tests on a cow basis. A new infection was defined as the transition between healthy and mastitic. Healthy was defined as a SCC not more than 200 000/ml, while mastitic was defined as a SCC above that level or as a case of clinical mastitis. Incidence rates were calculated with the herd size in cow-years in the denominator. Udder health data for the herd in the year 1997 were used in the analysis.

Statistical analysis

The association between technical specifications of the installations and the number of vacuum drops during milking was analysed in log-linear models for count-rate data (Agresti, 1996). Models were fitted by maximum likelihood estimation in SAS Genmod (SAS, 1996) procedures. The same procedures were used to analyse the association between the vacuum drops and udder health parameters. All variables used in the analysis are explained in Table 1.

RESULTS AND DISCUSSION

Repeatability

Five repeated series of vacuum drop recordings on two farms gave the results shown in Table 2. The hypothesis is that the number of vacuum drops in one milking under given conditions has a Poisson distribution, which implies a standard deviation (SD) equal to the square root of the average value. The measured values have a SD near to or less than could be expected from a Poisson distribution, and thus show repeatability to be as good as can be expected for count data.

Table 2. *Number of transient vacuum drops per milking. Data were collected in five consecutive milkings performed by the farm's regular milker on two farms*

(Values are means ± SD)

	NDROP2	NDROP5	NDROP8
Farm 1	17·8 ± 4·1	6·4 ± 2·4	2·6 ± 0·9
Farm 2	21·6 ± 2·7	2·6 ± 1·5	0·6 ± 0·9

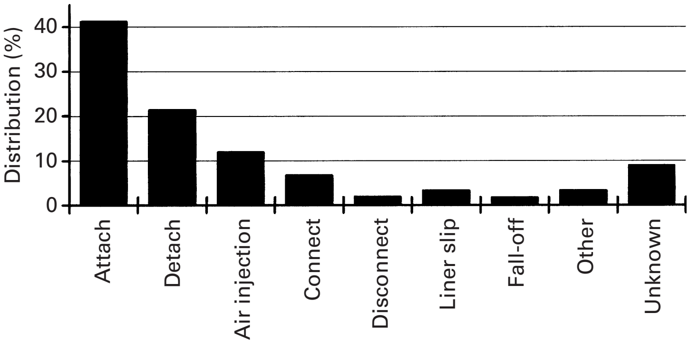

Fig. 3. Distribution of direct causes in a total of 371 vacuum drops $\geqslant 2$ kPa observed during one milking in each of 34 herds. Causes: Attach/Detach – vacuum drops appearing under attaching or detaching teatcup cluster; Air injection – drops coincident with deliberate air inlet in idle cluster; Connect/Disconnect – drops coincident with milking unit connection to or disconnection from the pipelines; Liner slip – drops coincident with audible liner slips; Fall-off – drops coincident with clusters falling off the udder.

Direct cause of vacuum drops

The field technicians were able to detect the direct cause of ~ 90 % of all vacuum drops during simultaneous observation of milking and the vacuum curves. Figure 3 shows that ~ 40 % of all vacuum drops occur during cluster attachment, and as many as 80 % during the operator's handling of the milking unit when changing from one cow to another. Undetected liner slips probably cause many of the drops with unidentified causes, so the real rate of liner slips may be substantially higher than indicated in Fig. 3. The magnitude of the vacuum drops (not shown) varies somewhat between the direct causes. The largest drops occur during cluster fall-offs and deliberate leakage of air into the cluster (average 5·0 and 6·2 kPa respectively). Liner slips result in the smallest vacuum drops (average 3·3 kPa).

Machine factors explaining vacuum drops in the milkline

Log-linear models were fitted for the frequency of vacuum drops exceeding 2, 5 and 8 kPa respectively. The following model was used:

$$\log\left(\frac{\text{NDROP}}{\text{REGTIME}}\right) = \alpha + \beta_1 \cdot \text{MLDIAM} + \beta_2 \cdot \text{MLLEN} + \beta_3 \cdot \text{MLSLOPE} + \beta_4 \cdot \text{UNITS} + \beta_5 \cdot \text{ER} + \beta_6 \cdot \text{VBMT}. \qquad \text{(I)}$$

(Repeated for NDROP = NDROP2, NDROP5 and NDROP8.)

The fitted coefficients are given in Table 3. They show that milkline dimensions and slope have the largest effect on large vacuum drops and the number of milking units has a large effect on the whole range of drops; the effective reserve affects the number of small drops.

Table 3. *Coefficients for the log-linear model fitted for transient vacuum drops of at least 2 (NDROP2), 5 (NDROP5) and 8 kPa (NDROP8), respectively*

	NDROP2	NDROP5	NDROP8
Milkline diameter (MLDIAM)	−0·0352†	−0·0645*	−0·0997**
Milkline length (MLLEN)	−0·0185***	−0·0217**	−0·0239**
Milkline slope (MLSLOPE)	−0·1159**	−0·1963**	−0·1989**
Number of milking units (UNITS)	0·2979***	0·3130*	0·3306*
Effective reserve (ER)	−0·0011†	−0·0008	−0·0000
Vacuum bulk milk tank (VBMT)	−0·2014	−0·2435	−0·1458

Statistical significance of regression coefficients: † $P < 0·10$; * $P < 0·05$; ** $P < 0·01$; *** $P < 0·001$.

The effects of the milkline diameter and slope support the findings of Reinemann *et al.* (1993), and the concept for sizing milklines in the new ISO 5707 standard (ISO, 1996*a*). The effect of the length of the milkline is negative, which means that long pipelines are associated with few vacuum drops. This seems to contradict the older standards and recommendations, for example, the Nordic recommendations for milking machine plants (Danish Dairy Board, 1988). However, the older standards were aimed at limiting average vacuum drop, while the new ones, and the present work, focus on transient vacuum drops. The positive effect of long milklines, found in the present investigation, may be explained by the fact that the large internal volume in long pipes, mostly occupied by air, has a damping effect on vacuum fluctuations.

The model predicts an increase of 35–39% in transient vacuum drops per extra milking unit as a result of increased load. The number of milking units determines to a large extent the milk flow rates and air consumption in the installation, both planned and unplanned (ISO, 1996*a*).

An adequate effective reserve has been regarded as the essential factor to keep a stable vacuum in the milking installation, and has been a major concern in defining standards for milking installations. Le Du (1980) demonstrated in laboratory tests that, within certain limits, there was a significant effect of the vacuum pump capacity on the vacuum stability when the system was challenged with a sudden inrush of air. Under field conditions, Mein *et al.* (1994) found that the number of vacuum drops at the receiver increased markedly when the effective reserve was reduced, provided the reserve was below a critical level. The results indicate that the number of transient drops of 5 kPa and above is reduced by 8% when the effective reserve is increased by 100 l/min. However, the data cannot give any clue to determining an optimal effective reserve.

The model shows that a vacuum bulk-milk tank, used as such, reduces the frequency of vacuum drops by 22%. It has been assumed that this is the effect of incorporating a large volume of air in the vacuum system, which has a damping effect on vacuum fluctuations. Le Du (1980) reported similar findings for a range of vacuum pump capacities in laboratory investigations.

Different effects of the independent parameters on small *v* large vacuum drops throw light on the mechanisms causing the drops. A typical vacuum drop caused by inadequate capacity of the milkline will happen when milk slugs trap air in a part of the milkline. For a short period, when air is still entering the milkline, the vacuum between the milk slugs will drop fast because air cannot pass the milk slugs, and a large vacuum drop may be measured on the milkline. The other typical situation causing vacuum drop is when an unplanned entry of air exceeds the available effective reserve. The installation will then not be able to evacuate the air as fast as

Table 4. *Association between new infection rate and predicted frequency of vacuum drops in the milkline corrected for differences between counties*

Dependent variable	Coefficient, β_1
Drops > 2 kPa (PDROP2)	0·0075†
Drops > 5 kPa (PDROP5)	0·0144†
Drops > 8 kPa (PDROP8)	0·0301†

Statistical significance of regression coefficient: † $P < 0{\cdot}10$.

Table 5. *Association between the incidence rate of clinical mastitis and the frequency of vacuum drops corrected for differences between counties and incidence of teat lesions*

Dependent variable	Coefficient, β_1
Drops > 2 kPa (PDROP2)	0·0177*
Drops > 5 kPa (PDROP5)	0·0400*
Drops > 8 kPa (PDROP8)	0·0856*

Statistical significance of regression coefficient: *$P < 0{\cdot}05$.

it enters, and the vacuum will drop in the whole installation. In this case the vacuum will not drop so fast because the large internal volume being affected will help to damp the fluctuation.

Vacuum drops and mastitis

The effect of the frequency of vacuum drops and the predicted and residual drop frequencies from the model (I) on udder health were analysed. Only the predicted values showed a statistically significant association with udder health. It is paradoxical that the predicted frequency of drops is a better estimator than the measured one. This is discussed later.

The following log-linear models were fitted for new infections and clinical mastitis:

$$\log\left(\frac{\text{NEWINF}}{\text{HSIZE}}\right) = \alpha + \beta_1 \cdot \text{PDROP} + \beta_{1,10}^{\text{COUNTY}}. \qquad \text{(II)}$$

$$\log\left(\frac{\text{NMAST}}{\text{HSIZE}}\right) = \alpha + \beta_1 \cdot \text{PDROP} + \beta_2 \cdot \text{LESION} + \beta_{1,10}^{\text{COUNTY}}. \qquad \text{(III)}$$

(Repeated for PDROP = PDROP2, PDROP5 and PDROP8).

Results in Table 4 show an association between new infection rate and frequency of vacuum drop. The results are in line with those of Rasmussen *et al.* (1999) who, in a field investigation, found that instability of vacuum in the milkline was the dominant factor associated with new infection rate.

Values for 2, 5 and 8 kPa thresholds are not directly comparable because there was a wider variation in the number of drops for the low threshold. To compare the effects, one can look at the effect of a change in PDROP of 1 SD. Results in Table 4 show that the new infection rate increases by ~ 5% if the frequency of vacuum drops is increased by 1 SD for all three variables tested.

The effect of vacuum drops on clinical mastitis, shown in Table 5, was stronger than that on new infections. An increase in drop frequency of 1 SD was associated with a 12–15% increase in the mastitis indicator, the higher value applying to drops of 8 kPa and more. The observed results fit well with those of Østerås & Lund (1988) who, in a field study, found that audible air influx into the cluster during attachment was the most important factor associated with *Staphylococcus aureus* infections.

Confounding variables appear in both models. County is a variable discriminating between districts and reflects different strategies for treatment of mastitis. The effect of this confounding variable is pronounced for clinical mastitis, but rather weak for new infection rate. A strong association between teat lesions and clinical mastitis was also seen in earlier investigations (Østerås *et al*. 1995). Inclusion of this parameter in the statistical models is often necessary to isolate the effect of other factors.

Choice of parameters representing vacuum instability

Vacuum stability in the milkline is influenced by many factors that might change over time, such as:

- Machine factors that can be assessed in dry tests. Examples of measures are dimension of pipes and effective reserve. These factors will be nearly constant over time.
- Load in the sense of air and milk flow. The load might vary with morning and afternoon milking and with season, but it is determined mainly by the number of milking units.
- The user factor is mostly a result of the milking routines, particularly when changing unit from one cow to another. As shown in Fig. 2, most vacuum drops derive from air leaks during the change. There is probably wide variation in operators' skills between farms, but also day-to-day variation within farms resulting from, for example, a change of operator. Measurements will also be biased because most operators will be influenced by the fact that their work is monitored.
- Random error in Poisson-distributed data is dependent on the number of events. Low counts, due to selection of a high threshold for detecting drops, result in a relatively high random error.

The association between udder health and predicted frequency of drops, contrary to the observed values, can give some idea of the relative importance of the various factors. The predicted value is the average frequency of drops on a given installation with average load and average operator. This value will be valid in the long term, and has shown to be a predictor for udder health. The observed values include additionally the effect of actual load and the actual user (who is believed to have a large influence on udder health) on the day of measuring, and should thus be a better predictor. Where this is not the case in the analysis, it must be because the measured values also include errors due to unrepresentative hydraulic load, biases due to untypical behaviour of the operator, and random errors in sampling.

One objective of the present investigation was to identify variables describing vacuum instability. Number of vacuum drops per hour may be a suitable variable. The threshold value for inclusion as a drop is an important part of the definition. In the present study, three different threshold values were tested. Statistical analysis shows no real difference between the tested thresholds. Only a weak indication, in favour of the highest threshold, was found for the association with udder health. The results might indicate that the number of drops with a high threshold level gives the best causal explanation of the effect on udder health, while the high sampling error for the high threshold more or less equals this effect in the total association, compared with lower thresholds.

For diagnostic use, one has to rely on results from one milking. According to what was found above, the number of vacuum drops from one milking has limitations as a descriptor for the long-term conditions. If only the results in Table 4 are considered, the count of drops exceeding 2 kPa would be the best variable for judgement after one milking. Taking into account earlier results (Rasmussen *et al.* 1999) and the associations between milking machine factors and vacuum drops in Table 3, the number of drops exceeding 5 kPa may be preferable.

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