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Effects of the design of a milking unit on vacuum variations during simulated milking

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The vacuum variations at the apex of an artificial teat during simulated milking were measured in a factorial-design laboratory test involving six cluster types, two internal diameters (13.5 mm and 16 mm) of long milk tube (LMT), three water flow rates (4, 6 and 8 l/min), simultaneous (4 × 0) and alternate (2 × 2) pulsation patterns and three pulsator ratios (60, 64, and 68%). Four of the six clusters were fitted with wide-bore tapered liners and represented all combinations of two claw volumes (150 or 420 ml) and two short-milk-tube bores (8.5 mm and 13.5 mm). Two clusters were fitted with narrow-bore liners (22 and 25 mm) that had large-bore short milk tubes and large claw volumes. The vacuum variations were expressed as mean vacuum at the teat-end during the b-phase of pulsation (TVB), mean vacuum at the teat end measured over complete pulsation cycles (TV), minimum vacuum measured over complete pulsation cycles (TVM) and amplitude of vacuum fluctuation measured over complete pulsation cycles (TVF). The highest level of TVB was recorded with wide-bore tapered liners. For a milking unit fitted with a wide-bore tapered liner TVF was reduced and TVM increased by increasing either the bore of the short milk tube or the volume of the claw. When the bore of the LMT was increased TVB, TV and TVF increased. Simultaneous pulsation gave higher TVB ($P < 0.001$) and higher TVF ($P < 0.001$) than alternate pulsation for all cluster types. The overall effects of altering pulsator ratio were significant but small in practical terms. There were significant interactions between cluster type and water flow rate and pulsation pattern for TVB, TV, TVM and TVF.

Keywords: Milking machine; simulation; vacuum

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Introduction

The vacuum variations at the teat end during machine milking depend on operating vacuum level, liner design, pulsation characteristics and on the complex two-phase flow of milk and air from the teats to the recorder jar, bucket or milk pipeline. Milking speed is proportional to the average vacuum under the teat during the milking phase of pulsation (b-phase) when the liner is open. This vacuum level depends on the vacuum drop due to the components between the vacuum pump and the teat end. Most modern parlour milking systems have large-bore milk pipelines and the vacuum variations or losses in the milk pipeline are low. The main vacuum losses occur from frictional losses in the connecting system from the teat to the milk pipeline during milk flow. It is difficult to record these losses in commercial milking machines, as the flow through individual liners is not known. For this reason vacuum losses in milking systems are usually measured in the laboratory where water is used instead of milk and the flow conditions from the teat are simulated by inserting artificial teats into the liners and water flow is controlled.

Nordegren (1980) studied the effect of different mechanical factors on cyclic vacuum fluctuations at the teat end and in the claw during the four phases of liner movement using a flow simulator. He showed that the vacuum fluctuations during liner closure were reduced when the internal diameter of the short milk tube (SMT) was increased from 6 mm to 14 mm. ISO (1996) recommends that the SMT should have a minimum diameter of 10 mm. Worstorff and Hollweck (1977), Spencer and Jones (1978) and Nordegren (1980) showed that the internal diameter of the long milk tube had a small influence on vacuum fluctuations at the teat end. While vacuum fluctuations at the teat end decreased almost linearly with claw volume, a bigger volume had a small and negative influence on the vacuum during the milking phase (Nordegren, 1980). The trend in commercial milking machines is towards increased claw volume. O’Callaghan and Gleeson (2003) showed that mean vacuum at the teat end was reduced when claw volume increased above 150 ml for wide-bore tapered liners.

Assuming that vacuum fluctuations during liner closure do not cause liner slippage or impede the liner from collapsing on the teat, rating milking systems based on vacuum fluctuations measured over full pulsation cycles may be misleading. In tests during cow milking Osteras and Lund (1980) found smaller vacuum fluctuations and a smaller vacuum decrease with low-line milking equipment compared with high-line equipment. The correlations between milk flow and decrease in vacuum and between milk flow and vacuum fluctuation were not significant for a low-line milking machine. Stewart (1997) developed a portable flow-simulator for field-testing milking equipment but it is not clear whether this system mimics the degree of vacuum fluctuations introduced by a milking cow. Operating vacuum should be related to the milking or liner-open vacuum and not, as is common practice, to the mean vacuum measured over complete pulsation cycles (Worstorff and Hollweck, 1995). While most manufacturers supply milking systems that give minimum fluctuations during the full liner-movement cycle the alternative design approach of reducing vacuum losses during the milking phase and allowing vacuum drops to occur during liner closure can give satisfactory milking (O’Callaghan and Harrington, 2000). During milk flow simulation tests O’Callaghan and Gleeson (2003) showed higher vacuum fluctuations and higher mean vacuum at the teat end with simultaneous pulsation compared to alternate pulsation for wide-bore tapered liners. It is important that drops in vacuum during liner closure do not cause liner slippage or impede the liner from collapsing on the teat. The objective of the present study was to measure vacuum variations in the milking phase and over complete pulsation cycles during simulated milking using a range of milking units.

Materials and Methods

The experiment was an unreplicated 6 × 3 × 2 × 2 × 3 factorial design, with six cluster types, three water flow rates (4, 6 and 8 l/min); two long milk tube (LMT) internal diameters (16 and 13.5 mm); two pulsation phases (simultaneous and alternate) and three pulsator ratios (60, 64 and 68%). A milking unit is a combination of a cluster type, a long milk tube and a pulsator. A pulsation rate of 60 Hz was used for all treatments. All tests were carried out with the flow simulator developed by O'Callaghan (2002). The main details of the clusters used in the tests are given in Table 1. A mid-level milking configuration with a milk lift of 1.6 m was used, the system vacuum in the milk pipeline was set at 50 kPa. Simultaneous measurements of vacuum were made, using vacuum sensors calibrated with a mercury manometer, at four locations — at the teat end, in the claw, in the pulsation chamber and in the milk pipeline. Both analogue and digital outputs were available on a computer attached to the signal conditioning unit linked to the vacuum transducers. The maximum, minimum and mean levels of vacuum were computed for measurements, averaged over four pulsation cycles, taken at the teat-end, in the claw, in the pulsation chamber and in the milk pipeline during the b-phase and the d-phase of pulsation and over a complete pulsation cycle (TV = mean at teat end; CV = mean at claw). Corresponding vacuum values were calculated during the b-phase of pulsation at the teat-end (TVB) and in the claw (CVB). The amplitude of vacuum fluctuation at the teat-end (TVF) and in the claw (CVF) was computed as the maximum minus minimum vacuum averaged over four pulsation cycles.

Genstat 5 Release 3.2 (1993) was used for analysis of variance with a model that included all main effects and their 2- and 3-way interactions. Higher-order interactions were assumed to be negligible.

Results

The average vacuum traces recorded during complete pulsation cycles for simultaneous and alternate pulsation are presented in Figures 1 and 2, respectively, for the six cluster types (Table 1) with a water flow rate of 8 l/min, a pulsator ratio of 68% and LMT bore of 16 mm. The results from the analysis of variance are summarized in Table 2 for all the main effects and for interaction terms that were significant for at least one dependant variable. Inspection of the vacuum traces showed that TVB and CVB were almost identical during the 'b-phase' of the

Table 1. Details of clusters used in milking units for simulation tests

Cluster	Liner	Claw volume (ml)	Bore of short milk tube (mm)	Barrel bore (mm)	
				Upper	Lower
1	Dairymaster 916s[1]	150	8.5	31.5	20
2	Dairymaster 916s[1]	150	13.5	31.5	20
3	Dairymaster 916s[1]	420	13.5	31.5	20
4	Dairymaster 916s[1]	420	8.5	31.5	20
5	Bou-matic R-10 Flo-Star[2]	323	11.1	22.0	19.5
6	De Laval 999007 03[3]	275	12	25.0	21.0

[1] Dairymaster Ltd, Causeway, Co Kerry, Ireland.
[2] Bou-matic, Madison, Wisconsin, USA.
[3] De-Laval, Tumba, Sweden.

pulsation cycle for all the treatment combinations shown. Except for cluster 1 the vacuum traces recorded at the teat-end and in the claw were identical. The mean values of TV and CV declined progressively as water flow rate increased and a simultaneous pulsation pattern gave significantly higher levels of TVB than the alternate pattern. Cluster type, internal bore of LMT, water flow rate and pulsation pattern all had significant ($P < 0.001$) effects on TV, CV, TVB, CVB and TVF. Pulsator ratio had significant effects on TV, CV and TVF but the effects were trivial.

There were significant 2-factor and 3-factor interactions for each of the variables measured.

All the significant interactions involved either pulsation pattern or water flow rate or both these factors in combination with the effects of cluster type and bore of LMT. Consequently the results are presented in terms of the latter two main effects and relevant interactions.

Effects of cluster type

There was more variation in TVB within cluster types with 4 × 0 than with 2 × 2 pulsation. With 4 × 0 pulsation (Figure 1) the TVB for clusters 1 to 6 were 43.0, 41.7, 38.9, 39.1, 35.7 and 39.2 kPa, respectively. The corresponding values of TVB with the

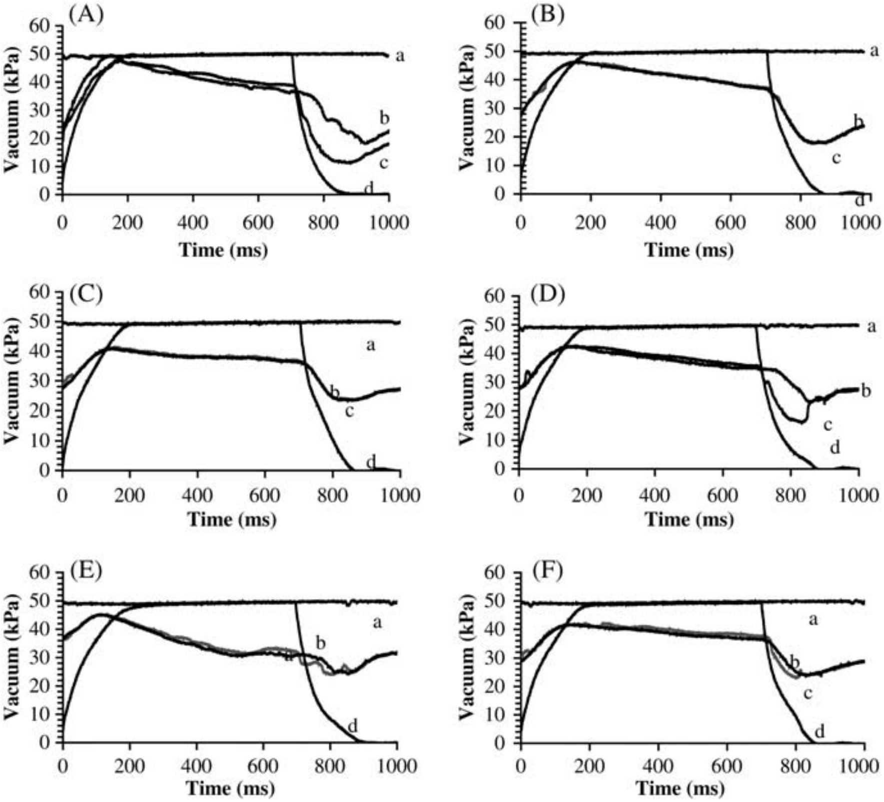

Figure 1: Vacuum traces at flow rate of 8 l/min with simultaneous pulsation pattern and pulsator ratio 68% for cluster 1 (A), cluster 2 (B), cluster 3 (C), cluster 4 (D), cluster 5 (E) and cluster 6 (F) showing system vacuum (a), claw vacuum (b), teat-end vacuum (c) and pulsation chamber vacuum (d). (See Table 1 for definition of cluster types).

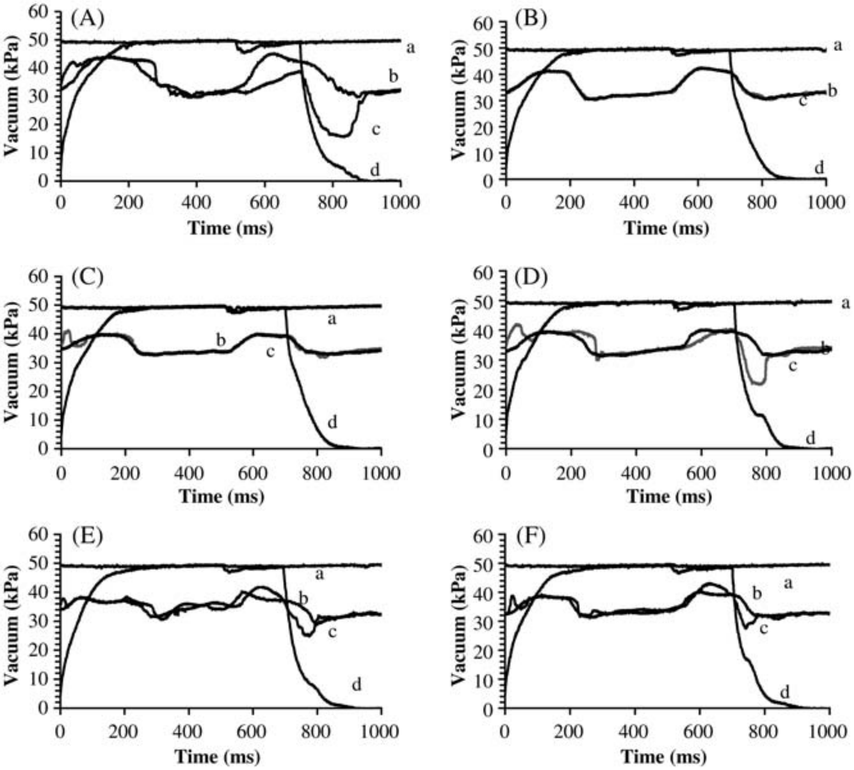

Figure 2: Vacuum traces at flow rate of 8 l/min with alternate pulsation pattern and pulsator ratio 68% for cluster 1 (A), cluster 2 (B), cluster 3 (C), cluster 4 (D), cluster 5 (E) and cluster 6 (F) showing system vacuum (a), claw vacuum (b), teat-end vacuum (c) and pulsation chamber vacuum (d). (See Table 1 for definition of cluster types).

Table 2. Summary of analysis of variance for the effects of cluster type, internal bore of long milk tube (LMT), flow rate, pulsation pattern and pulsator ratio on vacuum at the teat-end (TV) and in the claw (CV) over complete pulsation cycles and vacuum at the teat-end (TVB) and in the claw (CVB) during the b-phase of pulsation and on vacuum fluctuation at the teat-end (TVF)

Source of variation	F-test for effect on				
	TV	TVB	CV	CVB	TVF
Cluster type (CT)	***	***	***	***	***
Internal bore of long milk tube (LMT)	***	***	***	***	***
Flow rate (F)	***	***	***	***	***
Pulsation pattern (P)	***	***	***	***	***
Pulsator ratio (R)	***		***		**
CT × F	***	***	***	***	***
LMT × F	***	***	***	***	***
CT × P	***	***	***	***	***
LMT × P	*	***		***	*
CT × F × P	***	***	*	***	***
LMT × F × P		***		***	**

2 × 2 pulsation pattern were 35.3, 36.2, 35.7, 35.6, 35.6 and 35.5 kPa, respectively. TV of clusters 1 to 6 were 34.3, 35.4, 34.7, 34.2, 34.6 and 34.9 kPa, respectively, with 4 × 0 pulsation compared with corresponding values of 33.5, 35.7, 35.6, 34.9, 35.1 and 34.8 kPa, respectively, for a 2 × 2 pulsation pattern. Similar trends for clusters 1 to 6 were recorded at water flow rates of 4 l/min and 6 l/min. With 4 × 0 pulsation, TVB values were higher than TV for the six clusters. TVB and TV were similar with a 2 × 2 pulsation and the values were lower than with 4 × 0 pulsation.

For cluster 5 the reduction in TVB with increased water flow rate was lower than with the remaining cluster types but the differences between cluster types while significant were small in practical terms. The cluster type × flow rate × pulsation interaction for TVB is shown in Figure 3. A reduction in TVB occurred when water flow rate increased for all cluster types and both pulsation patterns. Cluster 5 gave a low TVB at 4 l/min with both pulsation patterns. The interactions of the six cluster types with flow rate and pulsation, while significant, were minimal in practical terms. The pattern of the corresponding interaction effects on CVB was similar. TVF for clusters 1 to 6 were 39.0, 29.0, 19.1, 26.1, 19.6 and 19.2 kPa, respectively, at a flow rate of 8 l/min and with 4 × 0 pulsation. (Figure 1). With 2 × 2 pulsation (Figure 2) the corresponding values for the six cluster types were 28.3, 12.9, 10.4, 20.7, 14.4 and 12.4 kPa, respectively. Similar variation occurred at water flow rates of 4 and 6 l/min. The highest level of TVF was recorded with wide-bore tapered liners, small SMT and small claw volume with 4 × 0 or 2 × 2 pulsation pattern.

Effects of bore of long milk tube

Increasing the bore of the LMT resulted in a significant increase ($P < 0.001$) in TVB and CVB. With 4 × 0 pulsation, a pulsator ratio of 68% and a flowrate of 8 l/min TVB means for clusters 1 to 6 were 38.8, 36.4, 31.0, 31.6, 31.4 and 34.5 kPa, respectively, for a 13.5-mm LMT and 43.0, 41.7, 38.9, 39.1, 35.7 and 39.2 kPa, respectively, for a

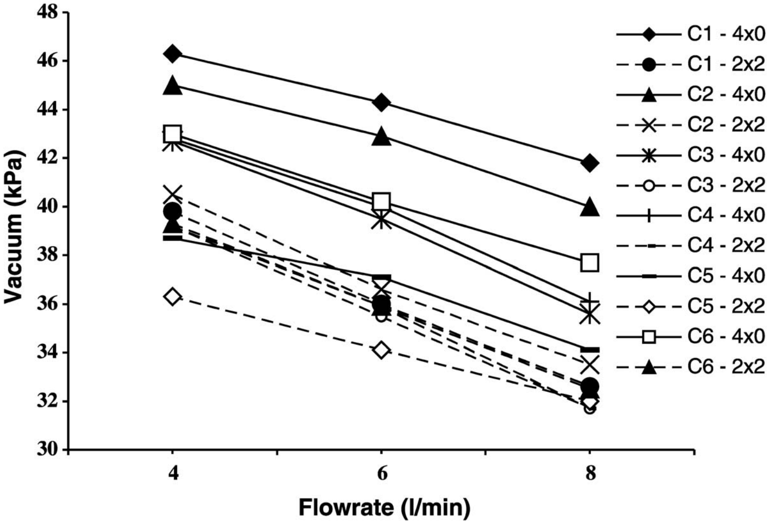

Figure 3: Interactions of cluster type (C1 to C6) with water-flow rate by pulsation pattern for mean teat-end vacuum during the b-phase of pulsation. (See Table 1 for definition of cluster types).

16-mm LMT. With 2 × 2 pulsation the corresponding values were 30.4, 31.4, 27.8, 28.2, 27.9 and 30.3 kPa, respectively, for a 13.5-mm LMT and 35.3, 36.2, 35.7, 35.6, 35.6 and 35.5 kPa for a 16-mm LMT.

The 2-way interaction for TVB involving bore of long milk tube and pulsation pattern was significant ($P < 0.001$) as shown in Table 3 but small in practical terms. A similar trend occurred for LMT × F × P interaction.

Discussion

In most published data on the relationship between milking time and vacuum level TVB has been assumed to be equal to TV. In the present study large differences between TVB and TV were recorded for all milking clusters when used with 4 × 0 pulsation pattern. Cluster 1 gave the highest level of TVB and TVF. This is in agreement with measurements by O'Callaghan and Gleeson (2003). The reduction in the magnitude of TVB and TV with increases in water flow is in agreement with most previous studies. Goff and Leonard (1978) also found an interaction between flow and pulsation type, simultaneous pulsation gave higher flow capacity than alternate pulsation. Clusters that had large claw volume and large bore of the SMT had the lowest amplitude of vacuum fluctuations in the claw and at the teat end with either 4 × 0 or 2 × 2 pulsation pattern. This result is in agreement with studies of Nordegren (1980), Goff and Leonard (1978) and O'Callaghan and Gleeson (2003). While the vacuum losses during the milking phase with cluster 1 were low, a low level of minimum vacuum and a large vacuum fluctuation occurred during liner closure with simultaneous pulsation. This resulted in a low level of vacuum to collapse the liner. The ability of a liner to collapse during the massage phase is related mainly to the barrel bore, elasticity and tension of the liner. O'Callaghan and Gleeson (1997) showed that complete collapse of wide-bore tapered liners was possible with a vacuum differential as low as 10 kPa. The trend in modern milking machines is to have the bore of the milk tube greater than 10 mm. While the cluster types with large bore SMT gave lower TVF the effect on TVB or TV was minimal and improvements in milking characteristics are unlikely in this situation. The large volume above the short milk tube with the wide-bore tapered liners used in clusters 1 to 4 may explain the marginal effect of bore of SMT on TVB. O'Callaghan and Harrington (2000) showed that satisfactory milking characteristics can be obtained with wide-bore tapered liners that have an SMT bore in the range 8.5 mm to 10 mm.

Table 3. Interaction of cluster type and internal bore of long milk tube (LMT) with pulsation pattern for mean teat-end vacuum during the b-phase of pulsation (s.e.d 0.16)

Factor	Pulsation pattern	
	Simultaneous	Alternate
Cluster type		
1	45.2	39.1
2	44.1	39.7
3	41.3	38.6
4	41.6	38.6
5	39.0	37.8
6	42.0	38.7
Internal bore of LMT (mm)		
13.5	40.8	37.0
16.0	43.6	40.5

Narrow-bore liners used in clusters 5 and 6 with lower volume may require a large bore of SMT. TVB was higher with 4 × 0 pulsation than with 2 × 2 pattern for five of the six cluster types, the exception was cluster type 5. With this cluster water entered the claw tangentially and the flow patterns were visually different compared to the other claw types that had perpendicular entries. The visual buffering that occurred with 4 × 0 pulsation in the 420-ml claw used in cluster type 3 and 4 did not occur with the claw used in cluster type 5. Flow patterns in the claw can therefore affect the teat-end vacuum.

The interaction between bore of LMT with flow and pulsation pattern for both TVB and CLB indicated the practical benefit of increasing the bore of the long milk tube to 16 mm with either simultaneous or alternate pulsation systems. This is in agreement with results of Worstorff and Hollweck (1977) and Spencer and Jones (1978). Brazil *et al.* (1998) showed an increase in claw vacuum and a reduction in vacuum fluctuation with 2 × 2 pulsation when the bore of the LMT was increased.

The optimum level of TVB to achieve satisfactory milking in a mid-level milking installation is not defined. In some situations where vacuum losses during the b-phase of pulsation are high the system vacuum or vacuum in the milk receiver is increased to compensate for the vacuum loss. Worstorff and Hollweck (1995) showed that milk yield is impaired with this approach. Most manufacturers of milking units attempt to reduce the amplitude of TVF and thus the trend for more use of 2 × 2 than 4 × 0 pulsation. Reinemann (2003) highlighted the fact that vacuum fluctuations in modern milking machines are a relatively unimportant factor in the success of the milking process. The present study showed that it is possible to achieve low levels of vacuum loss at the teat-end during the 'b-phase' of pulsation in the presence of large vacuum fluctation with a milking unit consisting of wide-bore tapered liners, a small-bore SMT, a large-bore LMT and 4 × 0 pulsation pattern. In situations where minimal vacuum fluctuations are preferred a milking unit with narrow bore liners, large-bore SMT and 2 × 2 pulsation pattern should be used.

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