DOI:10.3220/LBF1478788111000

Evaluation of teat-end vacuum conditions as affected by different pulsation settings in a quarter-individual milking system

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Abstract

The objective of this study was to determine the effect of pulsation on the teat-end vacuum behaviour in a quarter-individual milking system (QIMS). To meet this objective, simultaneous (SIM), alternating (ALT) and sequential (SEQ) pulsation were tested in a laboratory milking parlour. In the pulsation system SEQ four pulsators, instead of one (as in SIM) or two (as in ALT), are used. Unlike in SIM and ALT, the pulsation in each quarter is started individually. After pulsation is started in quarter one, pulsation will begin in the following quarters, each with a time delay of 25 % of the pulse duration with respect to the start of the previous quarter. Tests were performed at various flow rates (0.8 to 6.0 l/min) with the help of the wet-test method and the teat-end vacuum behaviour was observed. The lowest vacuum fluctuation of 4.4 kPa was recorded under SIM pulsation as well as the lowest vacuum reduction of 1.3 kPa. Both values were recorded at a flow of 4 l/min during the suction phase (b-phase). For SEQ and ALT pulsation, higher levels of vacuum reduction and fluctuation were measured during the suction phase at a flow rate of 4 l/min (SEQ: 7.6 / 1.8 kPa and ALT: 9.0 / 1.9 kPa). Consequently, it was concluded that SIM pulsation is the most appropriate pulsation setting when optimization for low vacuum reduction and fluctuation during the suction phase is demanded.

Keywords: *Quarter individual milking, Sequential pulsation, vacuum fluctuation, vacuum reduction, wet-test-method*

Zusammenfassung

Bewertung der Vakuumverhältnisse an den Zitzenspitzen bei unterschiedlichen Pulsationseinstellungen in einem viertel-individuellen Melksystem

Ziel dieser Studie war es, mögliche Auswirkungen unterschiedlicher Pulsationssysteme auf das Vakuum an der Zitzenspitze in einem viertelindividuellen Melksystem (VIMS) zu untersuchen. Hierfür wurde im Versuchsmelkstand mit Gleichtakt-, (GT) Wechseltakt-, (WT) sowie sequentieller Pulsation (SP) gemolken. Das Pulsationssystem SP besitzt dabei vier anstelle von einem (GT) oder zwei (WT) Pulsatoren. Im Vergleich zum GT und WT, wird bei SP die Pulsation viertelindividuell gestartet. Nach Beginn der Pulsation in Viertel eins werden die folgenden Viertel nacheinander mit jeweils 25 % zeitlicher Verzögerung der Pulsdauer in Betrieb gesetzt. Die Versuche wurden bei verschiedenen Milchflüssen (0,8 bis 6,0 l/min) mit der Nassmessmethode durchgeführt und dabei das Vakuum an der Zitzenspitze gemessen. Die niedrigste Vakuumschwankung in Bezug auf GT lag bei 4,4 kPa, wobei hier der niedrigste Vakuumabfall 1,3 kPa betrug. Beide Werte wurden bei einem Durchfluss von 4 l/min in der Saugphase (b) aufgezeichnet. Bezüglich SP und WT-Pulsation trat ein höherer Vakuumabfall in der Saugphase bei einem Milchfluss 4 l/min (7,6 / 1,8 kPa SP und 9,0 / 1,9 kPa WT) auf. Folglich ist die Gleichtaktpulsation (GT) die geeignetste Einstellung, wenn eine Optimierung für wenig Vakuumabfall und für kleine Vakuumschwankungen in der Saugphase zugrunde liegt. (VIMS = QIMS, GT = SIM, WT = ALT und SP = SEQ).

Schlüsselwörter: *Viertelindividuelles Melken, Sequentielle Pulsation, Vakuumschwankung, Vakuumabfall, Nassmessmethode*

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1 Introduction

The development of an alternating pulsator by Alexander Shields in 1885 was the first milestone in the development of an efficient milking machine. For many years, all milking systems have been equipped with at least one pulsator. The technology of milking machines and even of pulsators has been improved over the years, but the basic principle remains the same. The pulsation behaviour can have a significant influence on the vacuum reduction and fluctuation in a milking system. Unstable vacuum conditions, characterized by high vacuum reductions and fluctuations, were serious problems in the 1930s, when milking machines were first coming into frequent use. Therefore, as stated by O'Shea and O'Callaghan (1980), there was an increasing number of new infections, not only because of cyclic vacuum fluctuations due to vacuum instabilities but also as a result of increases in the "liner-slip rate" (air infiltration between the teat and the milking cluster) and "fall-off rate" (fall-off of the milking cluster from the teat). Furthermore, backwards streaming air during the opening of the teat liner caused accelerated air movement. This strong acceleration of the milk particles and their impact on the teat could damage the udder tissue. If cyclic and acyclic vacuum fluctuations coincide with air infiltration at the milking cluster, then the acceleration of the milk particles may be enhanced (Schlaiß, 1994). Aksen (2008) also reported that the occurrence of cyclic and acyclic vacuum fluctuations can negatively impact udder health. In this regard, Thompson et al. noted as early as 1978 that cyclic vacuum fluctuations alone do not constitute a risk to udder health. Nevertheless, Besier et al. (2016) made the following statement: "In conclusion, irregular vacuum fluctuations during milking combined with cyclic vacuum fluctuations and very high teat-end vacuum levels seem to increase the incidence of udder infection and to reduce milk flow rate. There is an impact on proper liner movement; the degree of massage on the teat end is decreased."

Hamann (1987) concluded that mastitis can be caused by improper milking techniques, such as inappropriate pulsation settings. Furthermore, Spencer et al. (2007) noted that the vacuum level and pulsation ratio are important operating parameters that affect the performance of milking machines. Thus, they tested a liner and the effects of its settings on milking performance by applying three different pulsation ratios, 60:40, 65:35 and 70:30, and found that the interaction between vacuum level and pulsation ratio had a significant effect on milking duration, peak flow rate, and average flow rate but not on milk yield (Spencer et al., 2007). Thus, according to the Agriculture and Horticulture Development Bord (2016), the pulsation ratio between the two phases (b-phase and d-phase), which describes the length of time each phase should last, should be between 50:50 and 70:30, with the ideal ratio being 60:40 in favour of the milking phase. Ratios above 70:30 are a cause for concern because teat damage is more likely to occur; at ratios below 50:50, the cows may be undermilked, and milking times may lengthen. However, there are still controversial debates regarding the optimal teat-end vacuum and pulsation settings (Agriculture and Horticulture Development Bord, 2016). European Patent EP 2 033 511 A2 (Petterson, 2009) describes a device for the measurement of the vacuum near the teat end and the control of that vacuum. In this invention, the vacuum measurement is focused on the head vacuum. The head vacuum is the vacuum state in the mouth piece chamber of the liner, which is responsible for holding the teat cup on the teat, especially at the end of the milking process.

By modifying the head vacuum in combination with the pulsation settings, the milking efficiency of a milking system can be controlled. In this invention, the collapsed state of the liner can be maintained for up to 10 seconds when pulsation is stopped. The objective of the patented device is to shorten the milking duration. Thus, this new invention leverages teat-end vacuum and pulsation control to improve the milking process. In addition, European Patent EP 1 186 229 B1 (Van den Berg and Beije, 2007) describes an individual-animal computer-controlled device. This system is able to control the milking phase, the release phase, and the vacuum level of the pulsator system. These patents demonstrate that there is a strong correlation between control technologies for milking systems and the pulsation settings. Neijenhuis et al. (2000) stated that quarter-individual pulsation systems might prevent overmilking and improve teat-end (tissue) condition. A recent study by Sterrett et al. (2013) was conducted to investigate the effect of a quarter-individual pulsation system on changes in the teat-end (tissue) conditions of cows. The authors compared a standard pulsation system with the Milpro P4C™ quarter-individual pulsation system manufactured by Milkline (Gariga di Podenzano, Italy), which can halt milking by stopping pulsation when there is no longer any milk flow from one of the quarters. Sterrett et al. (2013) came to the conclusion that the use of quarter-individual pulsation gave rise to a positive trend, but the authors did not find a significant effect on the teat-end condition. Reinemann (2010) also commented on the topic of different pulsation settings and suggested that although quarter-based control of pulsation and/or vacuum is possible in quarter-individual milking systems (QIMS), this technology is unlikely to merit commercial development because of its increased cost and complexity.

Some researchers hold the opinion that high teat-end vacuum levels, especially during the release phase of pulsation, lead to damage to the teat tissue. When a higher level of vacuum is applied at the teat, the teat cup liner folds together to a greater extent during the c- and d-phases. Rasmussen and Madsen (2000) reported that on average, milking at low vacuum levels of 26 to 30 kPa at the teat end increases the time-on-machine and the frequency of liner slip compared with milking at higher vacuum levels of 33 to 39 kPa. By contrast, milking at higher vacuum levels slightly decreases the time-on-machine (Reinemann et al., 2001) and increases the number of teat ends that are open after milking. These results were obtained using a constant pulsation setting. In the same study, during milking at a high teat-end vacuum level, the authors found that the amount of time required for the teat ends to close after milking was increased. Generally, the teat takes several hours to recover its full integrity, even following good milking conditions (Neijenhuis et al., 2001). This can cause problems with udder health because the channel inside the teat is much less protected against colonization by bacteria. The practical relevance is that cows are consequently more likely to become ill, which leads to increased costs for the farmer and causes considerable pain for the cows.

Gleeson et al. (2004) investigated the topics of machine milking and pulsation settings. They found that the teat tissue changes as a result of machine milking. Upon testing eight treatments, including two pulsator ratios, two pulsation patterns (SIM/ALT) and two cluster types, in a mid-level plant, they found no significant differences between the treatments for any of the teat influence parameters that were measured. By contrast, Hamann (1987) concluded that mastitis could be caused through sub-optimal specification of the milking technique, such as inappropriate pulsation settings. However, the teat-end vacuum can be adjusted indirectly with the aid of different pulsation settings (Ströbel, 2012). This is one advantage of a milking system in which it is possible to switch the pulsation setting between simultaneous (SIM), sequential (SEQ) and alternating (ALT) modes, even when the effect of the pulsation setting on the teat-end vacuum is small. Overall, the literature shows that it is important to consider the type of pulsation used in milking systems because, depending on its interactions with other machine settings, the type of pulsation applied has a relevant effect on the teat conditions of cows.

The QIMS used in this study operates differently from conventional milking clusters. The most important technical innovations of the QIMS are as follows: a quarter-individual tube guidance system; the cleaning and disinfection of the inside and outside of each teat cup in between milking cycles with an automatic washing unit; the possibility for sequential pulsation; and four vacuum cut-off valves, one for each udder quarter. As the name implies, this valve is able to automatically shut off the vacuum supply when one or more teat cups are kicked off by the cow (Rose and Brunsch, 2007). Another characteristic of the used QIMS is the integration of Biomilker® technology (Hoefelmayr and Maier, 1979) into the milking system. Biomilker® technology, with its periodic inlet of air during the release phase of pulsation, produces a low teat-end vacuum level during the release phase (d-phase) but also a very low vacuum reduction during the suction phase (b-phase). The purpose of the b-phase is to open the liner to receive milk from the udder. During this phase, the pulsation chamber of the teat cup is connected to the machine vacuum system. The purpose of the d-phase is to close the liner to use it as a massage tool. During the d-phase, the liner is closed and applies pressure to the teat end. Thus, blood coagulations are massaged to higher regions of the teat to ensure that they will have no negative impact on the teat health condition. Furthermore, each pulsation mode also includes a- and c-phases. In a plot of vacuum vs. time, these two phases simply represent the times when the liner is folded over the teat or is pulled away from the teat. Both phases consist only of the time delay between the triggering of the (often) electric pulsator and the mechanical impact on the liner and teat. The time required for the evacuation and filling of the pulsation chamber is included in a- and c-phases. More detailed information is given in the book by Tröger (2003).

In some QIMSs, it is possible to operate the system with either simultaneous, alternating or sequential pulsation. The system software enables the selection of one of these three alternative pulsation settings. SEQ is a pulsation system with four pulsators, instead of one (as in SIM) or two (as in ALT); one pulsator is used for each teat cup. Unlike in SIM and ALT, the pulsation cycle of each udder quarter starts later than that of the previous pulsator by 25 % of the pulsation period. Currently, SEQ is not often an available setting in the milking systems that are officially offered on the market. The scientific relevance of this study lies in improving the knowledge of these different machine settings and their effects on the vacuum during the b- and d-phases. In earlier studies, only the mean for each pulsation cycle was calculated. Knowledge about the effects of milking machine settings on teat-end vacuum is of practical relevance because this knowledge helps to guide the optimization of machine settings in a milking system.

Based on these considerations, the objective of this study was to compare the vacuum conditions at the teat end during milking under simultaneous (SIM), alternating (ALT) and sequential (SEQ) pulsation during the suction and release phases of the pulsation cycle. The teat-end vacuum is of critical importance for the health of the teat tissue. The hypothesis of this paper is that the chosen pulsation pattern exerts a strong effect on the teat-end vacuum conditions in the tested milking system.

2 Materials and Methods

2.1 Test set-up

In the test set-up, vacuum measurements were conducted using the wet-test method (ISO 6690, 2007) to evaluate the teat-end vacuum under different settings at various flow rates (ISO 5707, 2007). In total, 336 individual milking processes of approximately 10 s in duration were completed under SEQ pulsation, and 332 milking processes with the same milking duration were completed under the ALT and SIM pulsation settings. In all experiments, ISO artificial teats were used in the wet-test method for simulated milking in a laboratory milking parlour (ISO 6690, 2007) (Figure 1). The test liquid was water, which was used as a substitute for milk to simulate the effects on the milk flow. The flow rate was varied between 0.8 and 6.0 l/min during the experiments. As a flow simulator, four flow metres (Parker Hannifin Corporation, Cleveland, USA) installed on a board were used. Each flow metre allowed the flow rate, which ranged between 0.0 and 2.0 l/min, to be measured with an accuracy of ± 2 %. The liquid tank, the flow simulator and the artificial teats were connected with tubes. The four teat cups of the milking system were attached to a holder and connected to the artificial teats. The artificial teats were manufactured strictly in accordance with the specifications of ISO 6690 (2007). The

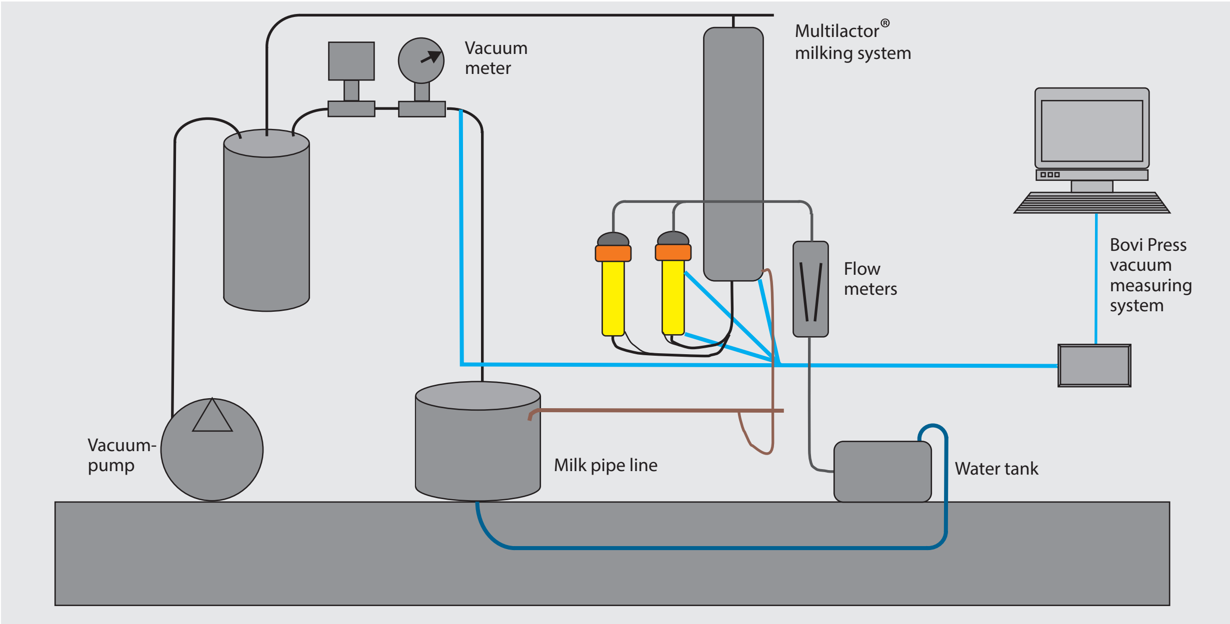

Figure 1

A schematic drawing of the QIMS used in this study, with the equipment for the wet-test method (modified according to Rose, 2006). The artificial teats were connected to the teat cups as shown in the middle of this figure. The pulse tube of the rightmost teat cup was connected to a vacuum sensor by 16-gauge injection needles, which are represented by blue lines. At each of the four points in the figure where a blue line meets a vacuum line, a pressure sensor was connected to the vacuum line at a distance of less than 10 cm. Point 1 was at the machine vacuum, point 2 was at the pulse tube of the teat cup pictured on the right and point 3 was at the teat end of the artificial teat to which the rightmost teat cup was attached.

test set-up, including the artificial teats, is depicted in Figure 1. A QIMS was used as the milking system in each test performed in this study. SIM, ALT and SEQ pulsation was applied using the QIMS in all tests. All tests were performed in a laboratory milking parlour – none of them was performed under farm conditions or with real cows.

Table 1

Technical details of the QIMS used in the laboratory milking parlour

Data	Value
Year of production	2008
Machine vacuum	35 kPa
Pulsation ratio	60/40
Pulsation rate	60/min
Construction of milking unit	quarter-individual
Milk tube length from teat cup to the Y-piece	3.095 mm
Inner diameter of the milk tube at the connection to the teat cup	10 mm
Style of air inlet	periodic air inlet via Biomilker® valve

The QIMS used in this study was developed in Germany. Other than the settings being tested, all other settings of the QIMS that were used during the tests, such as the pulsation rate, pulsation ratio and machine vacuum, were set to the levels recommended by the manufacturer (Table 1). All settings of the QIMS other than the tested parameters, namely, the pulsation setting and the flow rate, remained constant during the experiments. During each of the tests, the QIMS was operated in milking mode, and the four vacuum-cut-off-valves were deactivated. The different pulsation settings and the overall settings can be controlled using the control unit of the milking system (Table 1).

The vacuum was measured using a Bovi Press measuring system (A & R Trading GmbH Echem, Germany), which acquired samples at a rate of greater than 300 Hz and with an accuracy of ± 0.1 kPa. The measuring system stored the vacuum samples as DAT files (*.dat), which were renamed for each individual test by the laboratory staff and which could be opened for further statistical processing using MS Excel, MS Word and SAS (SAS Institute, Cary, USA). A measurement accuracy of ± 0.6 kPa is required by ISO 6690 (2007). Vacuum measurements were recorded over five pulsation cycles for each measurement at the end of the ISO teat (ISO 6690, 2007) in the pulsation chamber and in the machine vacuum line, simultaneously. The sensors were directly connected to the machine vacuum line and to the vacuum measurement point of each artificial teat (ISO 6690, 2007) to measure the teat-end vacuum. Furthermore, one sensor was connected with 16-gauge injection needles (BD Nokor Admix Kanüle 16G) to the pulse tube of one teat cup (Figure 1). The opening of each needle was oriented in the downstream direction. From the recorded data, the vacuum reductions during the b- and d-phases and the vacuum fluctuations during these phases were calculated for each of the five pulsation cycles in accordance with ISO 6690 (2007). Experiments were performed at various flow rates of 0.8, 2.0, 2.8, 4.0, 4.8, 5.6, and 6.0 l/min, where these flow rates are the sum of the flow rates for all four udder quarters. For each quarter, the flow was exactly 25 % of the total flow rate, and the flow rates for the four quarters were at the same level in each of the performed experiments. Each of the seven flow rates was tested in combination with each of the three pulsation settings, SIM, ALT and SEQ.

2.2 Statistical analysis

The recorded data were used to calculate the mean vacuum levels during the b- and d-phases of the pulsation cycle. For each repetition at each flow rate, the data from five selected contiguous pulsation cycles were considered, and the vacuum fluctuation (*vf*) in each phase was calculated as follows (ISO 6690, 1996):

$$vf_{phase} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(p\max_i - p\min_i \right)$$

where

i pulsation cycle,

$p\max$ maximum vacuum per pulsation cycle,

pmin minimum vacuum per pulsation cycle, and

n number of contiguous pulsation cycles ($n = 5$).

Furthermore, the vacuum reduction (*vr*) was calculated for each phase as follows (ISO 6690, 2007): Each measured vacuum value per pulse cycle was recorded, and the mean for each pulsation cycle was calculated. The difference was calculated between the mean sensor reading at the "machine vacuum" measurement point during each cycle and the mean value at the "teat-end vacuum" measurement point for that cycle.

The pulsation phases were identified using a SAS macro based on the formulae presented in ISO 5707 and ISO 6690 (2007). The effects on the vacuum reduction at the teat end were evaluated through parametric tests based on a linear model using the Proc MIXED procedure of SAS (SAS Institute, Cary, USA). To adjust for multiple comparison tests between factor levels, the SIMULATE option was used.

The linear model used was

$$\underline{y}_i = \mu + \alpha_i + \beta x + (\alpha\beta)_i\, x + \underline{e}_i$$

where

y_i vacuum reduction or vacuum fluctuation,

μ general mean,

α_i (fixed) effect of the i^{th} pulsation setting ($i = 1,...,3$),

β (fixed) effect of the covariate x (flow rate),

$(\alpha\beta)_i$ (fixed) effect of the interaction between the i^{th} pulsation setting and the covariate x (flow rate),

e_i independent normally distributed residual.

Pulsation settings 1 through 3 denote the alternating (ALT), sequential (SEQ) and simultaneous (SIM) pulsation settings, respectively. Three replications per quarter were performed for all pulsation settings at all seven flow rates ranging from 0.8 to 6.0 l/min, resulting in 336 observations for the SEQ setting and 332 observations each for the ALT and SIM settings.

3 Results

3.1 Vacuum reduction

From the calculated vacuum reductions during the b-phase (suction phase), it was found that at a flow rate of 4.8 l/min, the three pulsation settings (ALT, SEQ and SIM) exert a comparable effect on the teat-end vacuum reduction (Figure 2). However, at a flow rate of 4 l/min, the observations for SIM differ significant from those for the other two pulsation settings during both the b- and d-phases (suction and release phases). For this flow rate, the vacuum reductions observed during the b-phase for the ALT and SEQ pulsation settings are significantly higher than those for SIM (Figure 2), whereas the values observed during the d-phase are significantly lower for ALT and SEQ than for SIM (Figure 3).

It was found that in all cases for ALT and SEQ, the vacuum reductions are nearly identical, although in many cases, they differ considerably from those observed under the SIM pulsation setting (Figures 2 and 3). This is true for a flow rate of 2.0 l/min or lower, but it is not valid for flow rates higher than 4.8 l/min during both the b- and d-phases of the pulsation cycle (Figures 2 and 3).

In total, the values recorded during the b-phase indicate a maximum vacuum reduction of approximately 6.0 kPa (SIM) and a minimum reduction of -3.0 kPa (SIM), as seen from Figure 2. For the d-phase, the values indicate a higher maximum vacuum reduction of approximately 28 kPa (SEQ) and a minimum reduction of approximately 7.0 kPa (SEQ), as seen from Figure 3. Thus, during the d-phase (release phase), much higher vacuum reductions were observed at all flow rates and for all three pulsation regimes in comparison with the vacuum reductions during the b-phase (suction phase). This is expected because during the b-phase, a higher vacuum is required for milking the cow and for transporting the milk.

3.2 Vacuum fluctuation

The following wet-test results presented in Figure 4 and 5 for the three different pulsation settings during the b- and d-phase show that each of the three pulsation settings has a significant effect on the vacuum fluctuations in the milking system.

At a low flow rate of 0.8 l/min, the fluctuations during the d-phase were approximately three times higher than those during the b-phase. By comparison, at a higher flow rate of 6.0 l/min, the teat-end vacuum fluctuations showed values of between 4 and 10 kPa in both the b-phase and the d-phase (Figures 4 and 5).

The fluctuations observed under SEQ and SIM pulsation during the b-phase (Figure 4) show an approximately

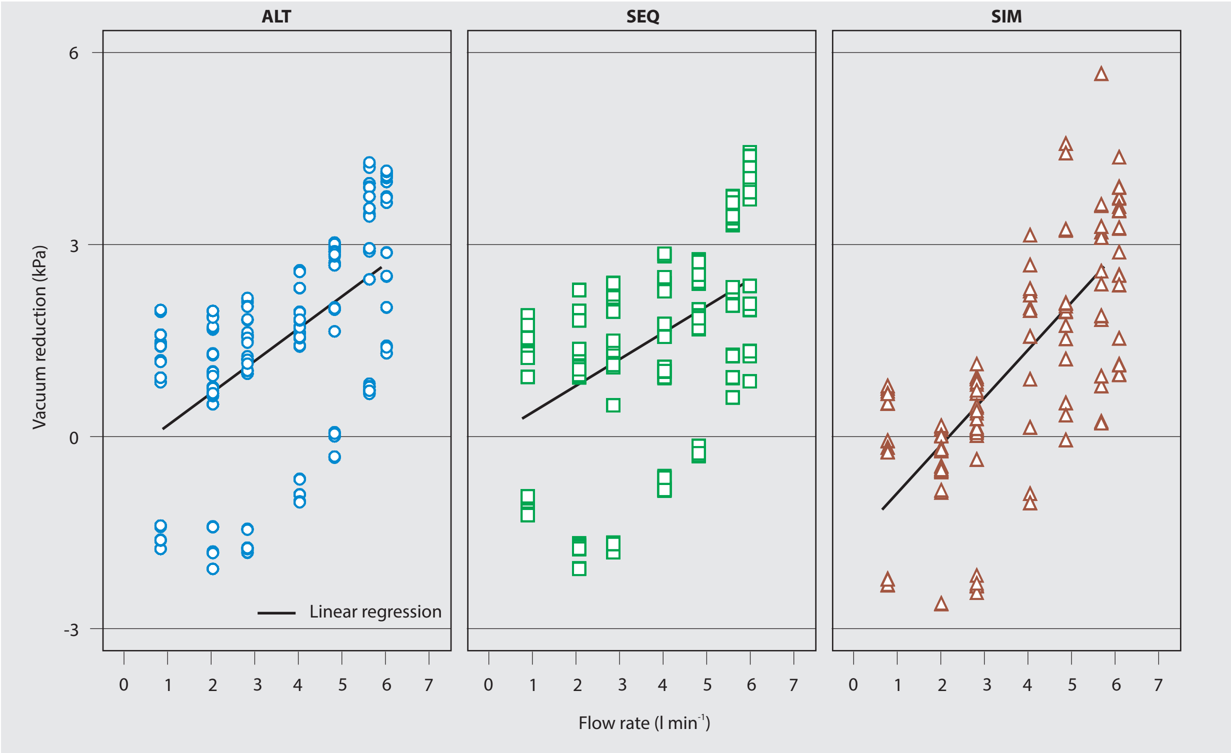

Figure 2
Vacuum reductions at the teat end during the b-phase of the pulsation cycle under the ALT, SEQ and SIM pulsation settings at various flow rates.

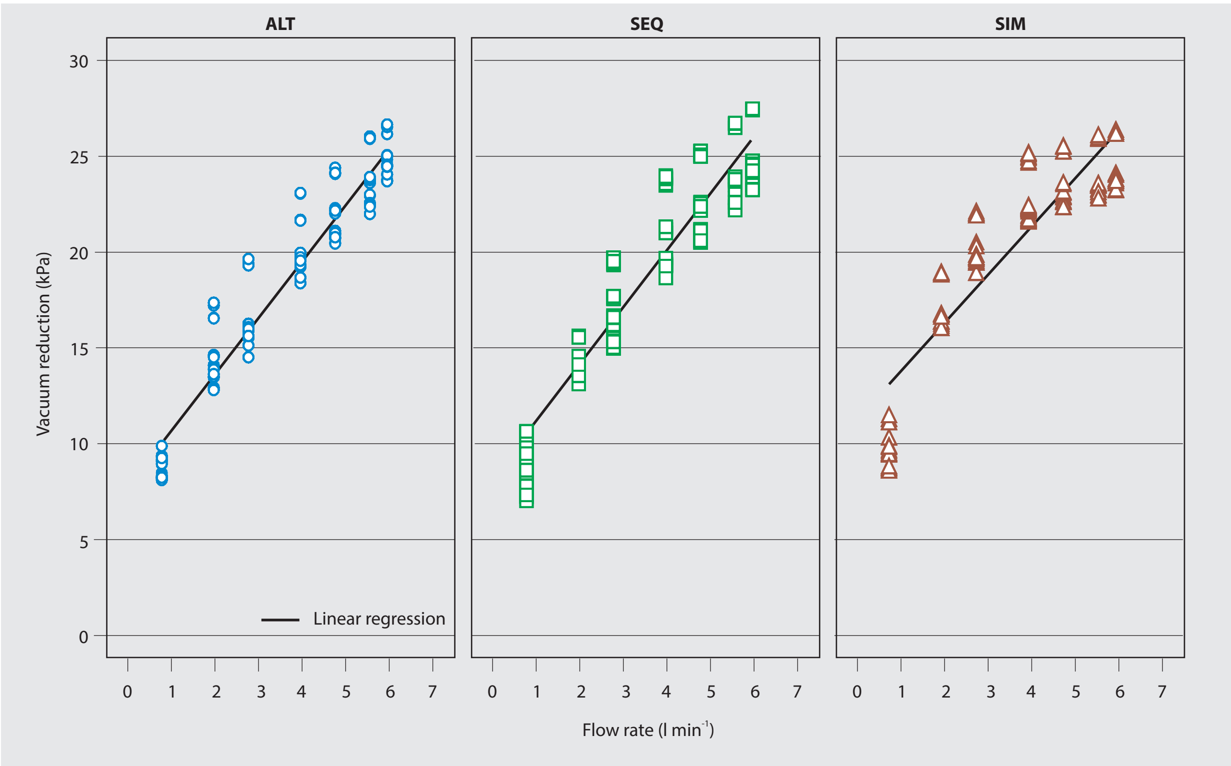

Figure 3
Vacuum reductions at the teat end during the d-phase of the pulsation cycle under the ALT, SEQ and SIM pulsation settings at various flow rates.

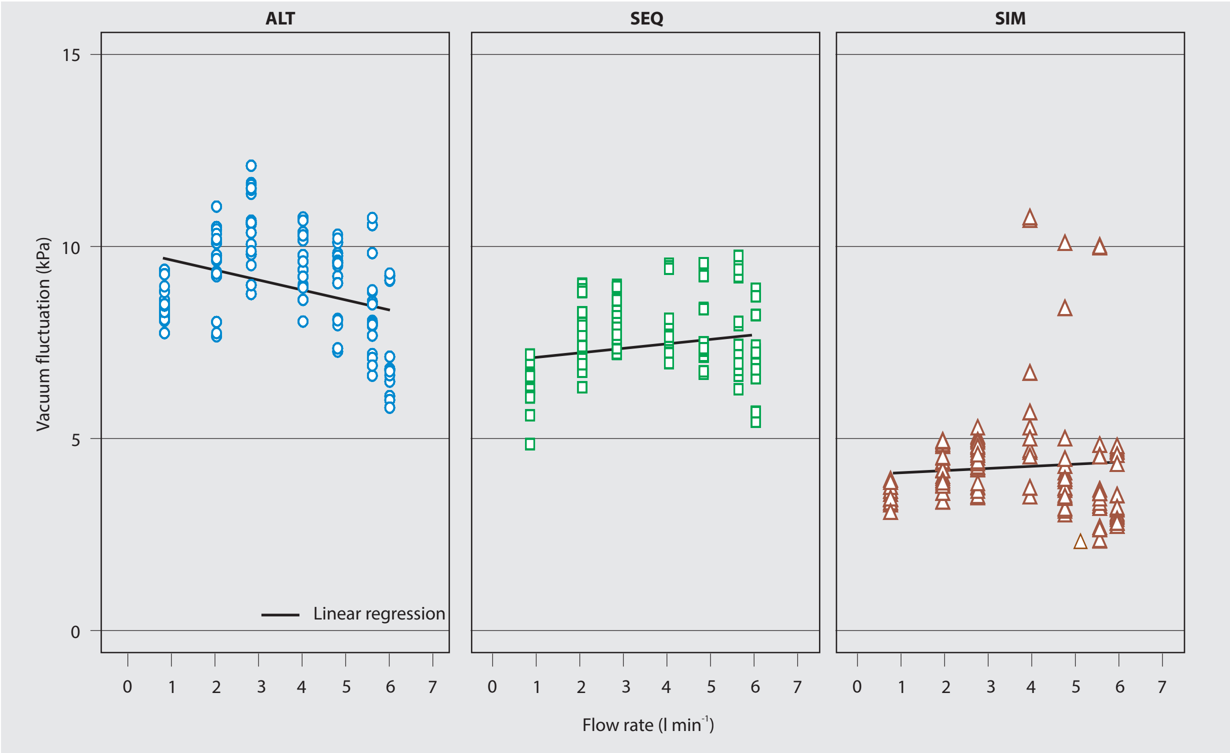

Figure 4
Vacuum fluctuations at the teat end during the b-phase of the pulsation cycle under the ALT, SEQ and SIM pulsation settings at various flow rates.

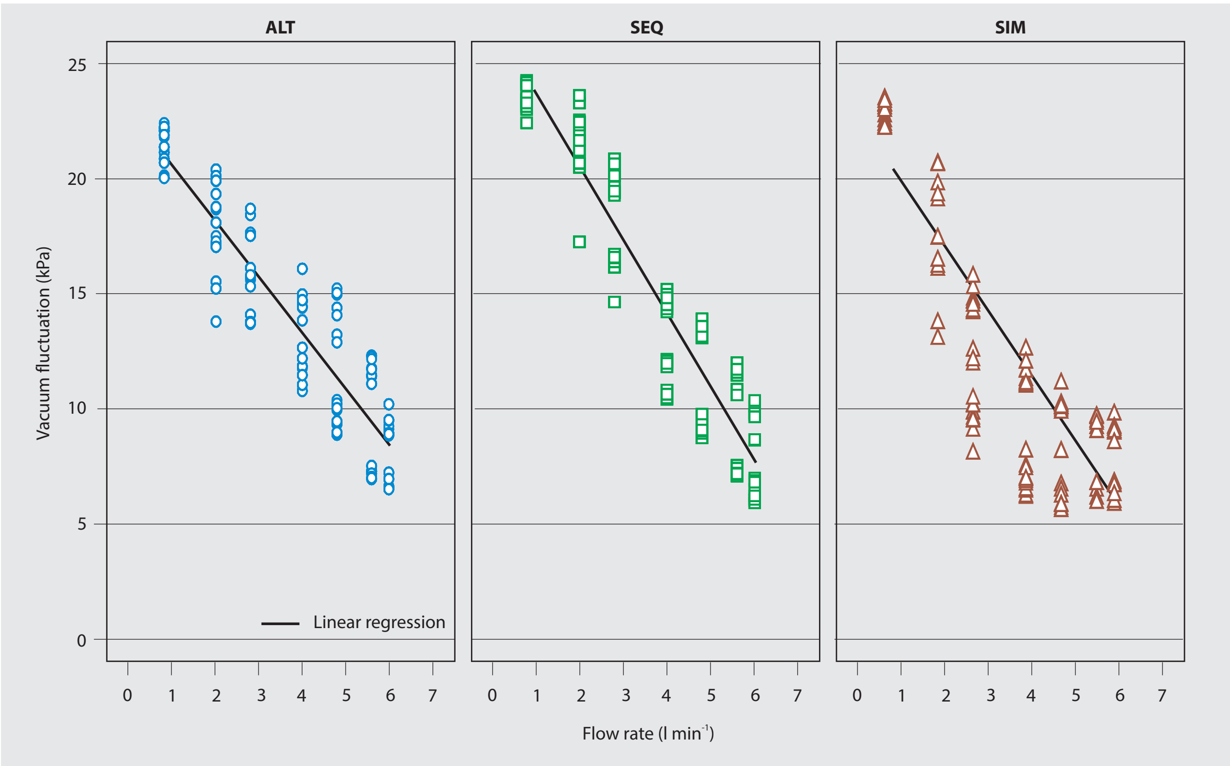

Figure 5
Vacuum fluctuations at the teat end during the d-phase of the pulsation cycle under the ALT, SEQ and SIM pulsation settings at various flow rates.

constant trend with an increasing flow rate. By contrast, for ALT pulsation, a moderately decreasing trend with an increase in the flow rate was found. For the b-phase, the ALT setting yielded the highest fluctuations at almost all flow rates, whereas the SIM setting yielded the lowest (Figure 4). The calculated regression line for the vacuum fluctuations during the b-phase under SEQ pulsation was found to lie between the other two regression lines (Figure 4).

For ALT, SEQ and SIM during the d-phase (Figure 5), a decreasing trend was observed with an increasing flow rate. This was true for the d-phase at all measured flow rates. The lower vacuum fluctuations during the d-phase at high flow rates (6.0 l/min) and the higher vacuum fluctuations at low flow rates (1.0 l/min) can be explained based on the development of the teat-end vacuum over the duration of the pulsation cycle. At low flow rates, the vacuum reductions during the d-phase that are induced by the pulsator arrive at the teat end very late in comparison to the case at high flow rates under otherwise identical conditions. Therefore, the range between the minimum and maximum vacuum values during the d-phase is much larger at low flow rates. During the c-phase, there is almost no vacuum reduction (Figures 4 and 5).

During the d-phase, the SIM setting yielded the lowest overall vacuum fluctuations at all flow rates, according to the regression lines. The SEQ setting yielded the highest d-phase fluctuations for liquid flow rates between 0.8 and 5.0 l/min (Figure 5). The results for ALT pulsation lie between those for SEQ and SIM, according to the regression lines, for flow rates of 0.8 to 5.0 l/min. At flow rates between 5.5 and 6.0 l/min, ALT and SEQ again yielded similar values for the teat-end vacuum fluctuations during the d-phase, whereas the SIM setting yielded moderately lower fluctuations.

3.3 *Statistical analysis*

The results of the wet tests regarding the effects of the pulsation setting, the flow rate, and the interaction between these factors on the vacuum reductions and fluctuations during the b- and d-phases are given in Table 2. The F test for heterogeneity revealed that both the flow rate and the interaction between the flow rate and the pulsation setting have significant effects on both the vacuum reductions and the vacuum fluctuations ($P < 0.0001$) in both phases (Table 2). A significant effect of the pulsation setting on the teat-end vacuum was found for almost all cases; the only exception was that the SEQ pulsation setting was not found to significantly affect the vacuum fluctuation in the d-phase. Furthermore, a significant effect of the interaction between the pulsation setting and the flow rate was also found for almost all cases, with the exception of the effects on the b-phase vacuum fluctuation of the interactions of the ALT and SIM pulsation settings with the flow rate.

The significant effects of the flow rate and pulsation setting show that increasing the flow rate will cause an increase in the vacuum reductions but not the vacuum fluctuations. Furthermore, for the significant interactions between the flow rate and pulsation setting, the slopes are similar for the effects of ALT and SEQ pulsation on the vacuum reductions in both phases, but both are different to the slope for the SIM pulsation setting. By contrast, a different picture was found for the vacuum fluctuations. During the b-phase, for SEQ and SIM, no increase in the slopes of the two regression lines was observed with an increasing flow rate. These two regression lines are nearly horizontal. For ALT pulsation, however, the slope of the regression line shows a decrease in the vacuum fluctuation with an increasing flow rate. By contrast, in the d-phase, all three pulsation settings led to a decrease in the fluctuations with an increasing flow rate.

4 Discussion

The hypothesis of this study was that each pulsation setting would produce significant differences in the teat-end vacuum conditions in the tested milking system. This hypothesis was found not to be true for all three pulsation settings. As

Table 2

Estimates (± s.e.) of the least-squares means † and the coefficients of regression on the flow rate for the vacuum reductions and vacuum fluctuations during the b- and d-phases of the pulsation cycle for three pulsation settings (ALT, SEQ and SIM) in a QIMS.

Effect	Vacuum reduction (kPa) in		Vacuum fluctuation (kPa) in	
	b-phase	d-phase	b-phase	d-phase
Pulsation setting				
ALT	2.10 ± 0.088	21.89 ± 0.117	8.72 ± 0.087	11.36 ± 0.142
SEQ	1.94 ± 0.086	22.16 ± 0.116	7.62 ± 0.086	11.55 ± 0.140
SIM	1.82 ± 0.086	22.94 ± 0.116	4.40 ± 0.086	9.27 ± 0.141
Regression on flow rate for				
Setting ALT	0.50 ± 0.042	2.95 ± 0.056	-0.25 ± 0.041	-2.44 ± 0.068
Setting SEQ	0.41 ± 0.041	3.02 ± 0.055	0.12 ± 0.041	-3.15 ± 0.067
Setting SIM	0.73 ± 0.041	2.51 ± 0.055	0.06 ± 0.041	-2.83 ± 0.067
F test for heterogeneity	<0.0001	<0.0001	<0.0001	<0.0001

† At a flow rate of 4.8 l/min

shown by the vacuum reduction results, the hypothesis is not true for the ALT and SEQ pulsation settings. The ALT and SEQ settings result in very similar teat-end vacuum reductions. However, significant differences were observed between the effects of both the ALT and SIM settings and the SEQ and SIM settings on the measured vacuum reductions, indicating that the hypothesis does hold for this subset of the results. Overall, the hypothesis was also confirmed regarding the effect of the pulsation setting on the vacuum fluctuations. Only the findings for SEQ pulsation during the d-phase did not differ from those for the other two settings in terms of the observed teat-end vacuum fluctuations. In the literature, several studies and arguments have been put forward to demonstrate that pulsation settings can affect the teat-end vacuum conditions in a milking system. For example, a milking system was developed in the 1990s that allowed the pulsation to be controlled throughout the entire milking process, with frequent alterations in the pulsation rate and ratio that depended on the measured milk flow data.

During the development and testing of that pulsator system, Ordolff (1991) found that varying the pulsation rate exerted effects on the liner movement, teat-end vacuum and strippings compared with earlier measurements in uncontrolled milking systems. However, it could not be ensured that the liner would completely collapse in that pulsator-controlled milking system. It permitted a pulsation ratio of up to 85 % in favour of the suction phase at the highest possible milk flow rates (Schlaiß, 1994). However, the teat-end vacuum was affected by different pulsation settings, as observed in the current study, in many cases. Those observations support the results of the current study. Concerning the suction phase (Figure 2), it can be postulated that ALT or SEQ pulsation is moderately superior to SIM pulsation for achieving effective and udder-tissue-preserving vacuum conditions at the teat end. Udder-tissue-preserving vacuum conditions are conditions in which the teat-end vacuum during the b-phase shows almost no vacuum reduction and the d-phase vacuum is as low as possible while still achieving sufficient massaging of the teat ends. In addition to the vacuum conditions at the teat end, many other parameters also influence the health of teat tissue, such as liner type and dimensions, milking duration, feeding, and seasonal effects. Moreover, one technical reason for Figure 4 and 5 is that the range of the different possible vacuum conditions at all possible flow rates is smaller under ALT and SEQ pulsation than it is under SIM pulsation. Thus, under the application of SIM pulsation, teat-end vacuum values could be measured that are much higher than the machine vacuum. However, this depends on the correct selection of the machine vacuum setting. If the machine vacuum is low, then SIM pulsation will be the better alternative; if it is high, then SIM pulsation will be a poor option because the overall vacuum applied at the teat ends of the cows will be too high.

If the release phase (Figure 3) is the focus of analysis, then SIM pulsation seems to be the better alternative because it was found that under SIM, especially at low flow rates, a moderately higher vacuum reduction is produced compared with the other two alternatives (ALT and SEQ). However, the difference in the vacuum reduction in the d-phase is relatively marginal. Thus, the effect in the b-phase is more important. Moreover, during the time interval of one pulsation cycle, it is not possible to make any adjustment to the pulsation settings. Therefore, the use of ALT or SEQ pulsation in the QIMS seems to be more appropriate than adjusting to the SIM pulsation regime. For this reason, it would be useful to develop a technical system that is capable of switching between pulsation settings at a high speed. Furthermore, the results of this study show that for all cases, the difference in the teat-end vacuum conditions produced by the ALT and SEQ pulsation settings is not large. Therefore, the QIMS can be operated under either ALT or SEQ pulsation almost equivalently. In a study by Gleeson et al. (2004), a slight (but not significant) difference was found in the teat tissue conditions measured via ultrasonography before and after the milking process under either ALT or SIM pulsation. Thus, there is no difference in the effect on the teat tissue between the two pulsation regimes.

It is also necessary to compare the teat-end vacuum conditions in the tested QIMS under ALT, SEQ and SIM pulsation with the corresponding conditions in other milking systems. O'Callaghan and Berry (2008) investigated a conventional cluster (CON) and a self-developed quarter-individual milking system (SD-QIMS) in a parlour with high-line installations. In this earlier study, the machine vacuum was 50 kPa for both the CON and SD-QIMS configurations. The vacuum reductions observed in the CON and QIMS cases can be compared with the reductions observed in this study during milking under ALT, SEQ and SIM pulsation at a flow rate of 4.0 l/min in the b- and d-phases. For the b-phase, reductions of 6.2 and 17.0 kPa were observed for the CON and SD-QIMS cases, respectively, whereas the mean reduction for the ALT, SEQ and SIM settings in this study was only 1.5 kPa. In the d-phase, a different trend can be found. The reductions were 11.5 and 25.0 kPa for CON and SD-QIMS, respectively, whereas the mean reduction for the ALT, SEQ and SIM settings in the QIMS was approximately 20 kPa. In comparison with the single teat cup unit investigated by O'Callaghan and Berry (2008), the pulsation regimes tested in the present study showed considerably lower vacuum reductions during the b-phase. The main reason for the desirably higher b-phase reductions of the CON and SD-QIMS configurations tested in the former study compared with the QIMS under different pulsation regimes in this study is that both systems considered in the earlier study were constructed with high-line installations. By contrast, the QIMS (for each pulsation regime) was equipped with a periodical air inlet system. Therefore, during the d-phase, the vacuum reductions in the SD-QIMS and the QIMS were more similar, whereas a greater difference was evident in the CON case. The differences between the milking systems led to much higher differences in the teat-end vacuum conditions compared with the differences between the three pulsation regimes (ALT, SEQ and SIM) in the QIMS.

Öz et al. (2010) showed that a modern conventional milking cluster with a 160 cm^3 claw volume induces fluctuations during the b-phase of between 4.0 and 5.0 kPa for flow rates between 0.8 l/min and 6.0 l/min per udder. The regression line for the SIM pulsation setting, which yielded the lowest fluctuations in the b-phase, lies between 4.1 and 4.3 kPa at the same flow rates. The other two pulsation regimes, especially ALT, yielded higher fluctuations in the b-phase. Data between 10.0 and 8.5 kPa were recorded for the ALT pulsation setting, and values between 7.3 and 7.6 kPa were found for SEQ pulsation. Thus, the comparison indicates that the QIMS under SIM pulsation shows similarly low vacuum fluctuations to those of the modern conventional milking cluster observed by Öz et al. (2010). In the QIMS, however, this is achieved by means of quarter-individual tube guidance because there is no vacuum buffer in the milk tube system, such as that provided by the claw in a conventional milking system.

Nordegren (1980), Schlaiß (1994) and Spohr et al. (1996) found that cyclic vacuum fluctuations have an effect on udder health. Thus, the higher b-phase vacuum fluctuations produced by the QIMS under ALT or SEQ pulsation may be a problem for some cows, even when the absolute values of the fluctuations are only moderately higher than those in the case of SIM pulsation. Tancin et al. (2006) found that vacuum modifications and proper preparation of the cows for milking can play an important role in ensuring a successful milking process. In addition, appropriate vacuum settings in combination with suitable preparations can greatly influence the milkability of the cows during the decline phase of the milk flow curves at the quarter level. The duration of the decline phase seems to be an important variable in the physiological response of dairy cows to milking machines (Tancin et al., 2006). Thus, the optimal pulsation regime and, with it, the optimal vacuum adjustment at the teat end in a milking system is essential for a successful milking process, with low vacuum fluctuations during the b-phase, a short decline phase and continuous milk ejection. As mentioned, the difference in vacuum conditions between the different pulsation settings of a milking system, when they vary widely, can be critical because an appropriate combination of a low vacuum reduction during the b-phase with a high vacuum reduction during the d-phase, as well as a proper massaging effect of the liner and high hygienic standards for milking, can help to optimize the milking process and protect the udder from inflammation and teat injury. When a cow becomes unprofitable because of illness, injury, reproductive inefficiency or low milk production, it is likely to be culled (Zavadilova et al., 2009). In this case, the farmer must cover the costs. Thus, it is very important for farmers to find the best pulsation regime for each milking system that exerts the most positive influence on the teat-end vacuum conditions during the suction and release phases, which are partially affected by the pulsation setting.

In addition to the effect of the pulsation setting, Tancin et al. (2007) showed in a study that milking without prestimulation negatively influences the milk flow, not only at the beginning of milking but also at the end of milking. The alveolar milk ejection induced by the release of oxytocin in response to machine milking throughout the entire milking procedure is an essential factor in ensuring fast and complete milk removal in dairy cows (Tancin and Bruckmaier, 2001). For example, stress caused by pain from an excessively high vacuum at the teat end can disturb milk removal and thus hinder a successful milking process. Therefore, the pulsation regimes of each milking system should be tested, and it should be ensured that at the beginning of the milking process, the open teat will not be exposed to high vacuum values of 45 kPa or more, which can cause pain for the cow and cause the stimulation process to cease. However, a low vacuum at low flow rates in milking systems is possible only when the vacuum reduction at the highest flow rates is not too great, as is the case for the ALT, SEQ and SIM pulsation settings in the QIMS, because a high vacuum reduction in combination with a low machine vacuum leads to frequent teat cup fall-offs, which farmers cannot accept.

A technical reason for the finding that the SIM setting results in lower vacuum reduction may be that in SIM pulsation, all b-phases in each of the four quarters begin at the same time. This leads to the summing of the vacuum fluctuations in all four quarters of a milking cluster, resulting in higher vacuum fluctuations, especially during the d-phase of the pulsation cycle. However, in the QIMS, in which the milk tubes cover a greater length before the tubes from all four quarters meet, no such cluster effect was observed. Moreover, lower or similar vacuum reductions were observed under SIM conditions compared with SEQ and ALT. The authors believe that the technical reason that this additive effect on the fluctuations was avoided is, as mentioned, the comparatively long milk tubes in the QIMS (3.095 mm).

5 Summary and Conclusions

QIMSs, especially those that offer ALT or SEQ pulsation, are a relatively new class of products on the market. By virtue of their quarter-individual tube guidance, these systems have the potential to offer solutions for several common problems encountered with regard to milk production in milking parlours. Tests conducted to observe the effects of three pulsation settings on the teat-end vacuum conditions show that the milking system should preferentially be used in the ALT or SEQ pulsation regime, which leads to a lower range of vacuum reductions during the suction phase. However, for some applications, when low vacuum fluctuations during the suction phase are desired, the use of SIM pulsation could also be advantageous for farmers. Compared with the differences in the vacuum conditions that exist between differently constructed milking systems (with different geometric configurations), the differences between the ALT, SEQ and SIM pulsation regimes are minor, although these differences are significant. The authors expected to find larger differences in vacuum when they defined the hypothesis for this paper. Based on a comparison of all findings, the authors believe that both the ALT and SEQ settings can help to improve the udder health of a dairy herd, or at least that these settings will help to guarantee that udder health will not deteriorate. In many cases, under all three pulsation settings, the tested QIMS generates a stable vacuum curve with a distinct vacuum reduction at the teat end during the release phase. Thus, it can contribute to reducing the stress on the teat tissue, as is required for modern animal-friendly milking systems. A construction proposal for the designers of the QIMS is to improve the QIMS by allowing it to choose the most suitable pulsation setting autonomously. This could be achieved by inserting a pressure sensor into the milk tube for each quarter. The installation of such sensors would allow the mean teat-end vacuum in each quarter to be calculated automatically. With the additional installation of decision-control software, the QIMS would be able to autonomously decide which pulsation setting is the best for each milking stall in the parlour. Moreover, the pulsation setting could be changed after the milking of each cow depending on the cows' individual milking characteristics.

Acknowledgements

The study and the associated research project were funded by the Federal Agency for Agriculture and Nutrition (BLE), which serves as a management agency for the Federal Ministry of Food and Agriculture (BMEL) as a result of a resolution by the German Bundestag. The authors acknowledge BLE and BMEL for providing comprehensive support for the project. Furthermore, the authors would like to thank Siliconform GmbH for providing the milking system and the software for controlling its different pulsation settings.

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