Teat Anatomy and its Relationship with Quarter and Udder Milk Flow Characteristics in Dairy Cows

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ABSTRACT

Anatomical and functional characteristics of the teat are supposed to have considerable influence on milk flow performance. In the present study, various teat and milking characteristics in 148 quarters of 38 cows were analyzed via 3 different approaches. Teat canal length, teat wall thickness, and teat diameter were measured by ultrasound. In addition, the vacuum needed to open the teat canal (VO) was determined and milk flow profiles were measured in each quarter separately.

Rear teats were shorter and thicker than front teats, whereas teat canal length and teat wall thickness did not differ according to quarter position. Milk yield and peak flow rate (PFR) were higher in rear than in front quarters. Teat canal length and VO were negatively correlated with PFR and average flow rate (AFR) but no correlations were observed between milkability traits and externally measurable teat characteristics like teat length or teat diameter.

Individual milkability at an udder level is a complex characteristic that is determined by the milkability at a quarter level and the distribution of quarter milk yields. The anatomical and functional characteristics of single teats can partly explain the milk flow characteristics of individual quarters.

(**Key words:** teat anatomy, teat canal, milk flow)

Abbreviation key: AFR = average flow rate, PFR = peak flow rate, VO = vacuum needed to open the teat canal, VO-C = vacuum needed to open the teat canal at cessation of milk flow, VO-S = vacuum needed to open the teat canal at start of milk flow.

INTRODUCTION

During machine milking, the teat represents the interface between the mammary gland and the teat cup liner. Therefore, the anatomical and functional

characteristics of the teat would be expected to have considerable effects on milking performance of the individual quarter and cow. According to earlier studies, teat canal measurements are related to the peak flow rate (PFR) (Baxter et al., 1950; Andreae, 1958; Loppnow, 1959). Besides milkability, the anatomy of the teat canal is related to udder health. Grindal et al. (1991) demonstrated an increased infection risk in quarters with short teat canals. In most studies, milk flow was analyzed based on an udder or half-udder level (Rogers and Spencer, 1991; Le Du et al., 1994; Slettbakk et al., 1995), although there is a considerable variability in milk flow profiles between the quarters within one udder (Rothenanger et al., 1995; Wellnitz et al., 1999; Weiss et al., 2003). To the best of our knowledge, there is no information available on the relationship between quarter milking characteristics and teat morphology at a quarter level.

The aim of the present study was to demonstrate possible relationships between teat anatomy and functionality using 3 different approaches. Teat anatomy was determined by ultrasound cross-sections. Milk flow profiles at a quarter level were recorded and the vacuum needed to open the teat canal (VO) was measured. The hypothesis was then tested if characteristics of the teat considerably influenced the milking characteristics.

MATERIALS AND METHODS

Animals and Milking

The 38 experimental cows (Brown Swiss × German Braunvieh) were in mo 1 to 8 of their first to fifth lactation. The diet consisted of corn and grass silage, hay, and concentrate according to the individual production levels. The cows were kept in loose housing and were milked in a 2 × 2 tandem milking parlor. Milking was performed twice daily at 0500 h and 1600 h at a vacuum of 40 kPa, a pulsation rate of 60 cycles/min, and a 60:40 pulsation ratio using a low line system. The milking routine consisted of udder cleaning and stripping of the first milk squirts in addition to manual prestimulation. The teat cups were attached 1 min after the first touch of the udder. For each quar-

Received March 23, 2004.

Accepted May 25, 2004.

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Figure 1. Ultrasound cross-section of one teat. The longitudinal section of the teat canal represents the scan axis. Anatomical characteristics were determined as described in the figure.

ter, teat cups with an individual ventilation system (Bio-Milker, WestfaliaSurge GmbH, Oelde, Germany) and with separate long milk tubes were used. At the end of milking, stripping was applied when total milk flow decreased below 0.3 kg/min.

Experimental Design

All experiments were performed during evening milkings starting at 1600 h. Teats were scanned by B-mode ultrasonography as described previously (Bruckmaier and Blum, 1992; SonoVet 2000, 5 MHz linear array scanner probe Nr. LV4-7AD, Kretztechnik, Zipf, Austria). Cross-sections of the teats were performed after a 1-min manual prestimulation, i.e., at a well-filled teat cistern. Teats were dipped in a plastic cup filled with water and the probe was attached to the cup wall using an ultrasound gel. The teat canal was used as the longitudinal scan axis. From the ultrasound images, the teat canal length, teat wall thickness, and teat diameter were determined as indicated in Figure 1. A gauge was used to determine the teat length from the teat tip to the teat base.

Milk flow was recorded for individual quarters using 4 mobile recording units (Lactocorder, Werkzeug und Maschinenbau Balgach, Balgach, Switzerland) as previously described (Wellnitz et al., 1999). The milk flow parameters were evaluated at a quarter and an udder level, according to Bruckmaier et al. (1995). Plateau and decline phases of the milk flow curves were determined based on the slope of the milk flow profile, as previously described by Göft (1992a, b). The decline phase lasted from the end of the plateau phase until the milk flow dropped below a threshold of 0.3 and 0.1

Figure 2. Device to determine the vacuum needed to open the teat canal; the vacuum was gradually increased until milk flow was visible, and subsequently decreased. The start and stop of the milk flow was marked within the recorded vacuum curve by pressing the switch of the handle bar.

kg/min at an udder and a quarter level, respectively. Main milking time was defined from the start of milking until the end of the decline phase. Average flow rate (AFR) was calculated as quotient of main milk yield and main milking time. Milk flow recording was performed during 2 evening milkings in each cow and means were used for further correlation analyses.

A special device based on a previously described approach by Le Du et al. (1994) was developed to determine VO. A transparent teat cup was equipped with the mouthpiece of a liner to avoid air leakage between teat cup and teat (Figure 2). The vacuum in the teat cup was gradually increased until milk flow was visible, and was subsequently decreased again (Figure 3). A vacuum measurement device was used to record the vacuum within the teatcup throughout the measurement (BoviPress, A&R Trading GmbH, Echem, Germany). The handle of the teat cup was equipped with a switch to mark the start and stop of milk flow within the recorded vacuum curve. The VO was measured after forestripping and the application of a 1-min manual prestimulation to ensure the start of milk ejection. Measurements were performed on the 4 quarters anticlockwise, starting at the left front teat. The VO measurement within one quarter lasted for about 7 s, as shown at a representative vacuum profile of one cow (Figure 3). Therefore the total measuring cycle, including the handling time, was 30 to 60 s for one udder. For calculation of the repeatability, the measurements were performed in each animal on 3 d.

Figure 3. Vacuum curve during the determination of the vacuum needed to open the teat canal (VO) and additional closure of the teat canal. The order of the tested quarters was left rear, left front, right rear, and right front. Measurements were done after forestripping and the application of 1-min prestimulation. The black arrow indicates the start of the milk flow, and the gray arrow indicates the cessation of the milk flow.

Statistical Analysis

The results are presented as means $\pm$ SEM. For statistical analysis, the SAS program package release 8.01 (1999; SAS Institute, Inc., Cary, NC) was used. The mixed procedure was used to determine significant effects. Differences were localized with student's *t*-test. The model included the quarter nested within the animal and the date of the measurement. The quarter within the animal was defined as a repeated factor, and the date was defined as a random factor. The REG procedure was employed to calculate Pearson's coefficients of correlation between the analyzed parameters. Results were indicated as statistically significant at $P < 0.05$, unless stated otherwise. The data contained information on 148 quarters of 38 cows; 4 cows were only milked on 3 teats due to previous mastitis in one quarter. Repeatability within the teat was calculated for VO according to Essl (1987).

RESULTS

Teat Anatomy

Front teats were longer than rear teats (Table 1). The diameter of the front teats was smaller than that of the rear teats. Teat wall thickness and teat canal

length did not differ significantly between front and rear quarters.

Vacuum Needed to Open the Teat Canal (VO)

The repeatability of vacuum needed to start the milk flow (VO-S) and vacuum at the cessation of the milk flow (VO-C) was 0.71 and 0.87, respectively. Values of VO-S and VO-C did not significantly differ between teat positions (Table 2). The value of VO-C was lower than VO-S, but VO-S and VO-C were correlated on a highly significant level ($r = 0.82$, $P < 0.0001$).

Table 1. Teat anatomy at a quarter level.

	Teat length (mm)	Teat diameter (mm)	Teat wall thickness (mm)	Teat canal length (mm)
Left front	66 $\pm$ 1.5 ^a	27 $\pm$ 0.4 ^{a,b}	8 $\pm$ 0.3	11 $\pm$ 0.3
Right front	67 $\pm$ 1.6 ^a	27 $\pm$ 0.4 ^a	8 $\pm$ 0.3	11 $\pm$ 0.3
Left rear	57 $\pm$ 1.5 ^b	28 $\pm$ 0.4 ^b	7 $\pm$ 0.2	11 $\pm$ 0.3
Right rear	56 $\pm$ 1.6 ^b	28 $\pm$ 0.3 ^b	7 $\pm$ 0.2	11 $\pm$ 0.3

^{a,b}Means with different superscript letters indicate significant differences between quarters ($P < 0.05$).

Table 2. Vacuum needed to open the teat canal at the start of milk flow (VO-S) and at the cessation of milk flow (VO-C).

	VO-S (kPa)	VO-C (kPa)
Left front	17.8 ± 0.9 ^a	7.1 ± 0.5 ^b
Right front	19.5 ± 0.8 ^a	7.9 ± 0.4 ^b
Left rear	20.3 ± 0.9 ^a	8.6 ± 0.5 ^b
Right rear	21.0 ± 0.9 ^a	8.9 ± 0.5 ^b

^{a,b}Means with different superscript letters indicate significant differences between vacuum at the start of milk flow and vacuum at the cessation of milk flow ($P < 0.05$).

Milking Characteristics

Figure 4 shows an exemplary udder and quarter milk flow profile. Peak flow rate, duration of the plateau phase, duration of the decline phase, and machine stripping are indicated at a quarter and an udder level. The start of the plateau phase was similar at a quarter and an udder level. However, the end of the plateau phase at a quarter level was determined by the availability of milk in the specific quarter, whereas the end of the plateau phase at an udder level was determined by the plateau length of the shortest milking quarter. The decline phase lasted until cessation of milk flow in the slowest milking quarter. The milking characteristics referring to the quarters are shown in Table 3. Total milk yield was 13.10 ± 0.45 kg, and total stripping yield was 0.25 ± 0.04 kg. Milk yield was higher and milking time was longer in rear compared with front quarters. Stripping yield did not differ between quarters. Peak flow rate and AFR were lower in front compared with rear quarters.

Results of the plateau and the decline phase are presented in relation to the respective main milking time. Relative plateau phase was shorter in front than in rear quarters, whereas the decline phase was longer in front quarters. At an udder level, the relative plateau phase ($30.1 \pm 1.8\%$, $P < 0.05$) was shorter compared with a quarter level. Consequently, the relative decline phase ($40.4 \pm 1.8\%$, $P < 0.05$) was prolonged at an udder level compared with a quarter level (Table 3).

Correlations

Pearson's coefficients of correlation at a quarter level are presented in Table 4. Teat wall thickness was positively correlated with teat diameter and teat canal length. No relationship was observed between teat length, teat diameter, and teat canal length.

Values of VO-S and VO-C were closely correlated; furthermore, VO-S and VO-C did not differ in their relationship to all other investigated parameters. There was no correlation between VO and any anatomical parameter.

Milk yield was positively correlated with main milking time, plateau phase, and AFR, but negatively with decline phase. Stripping yield was not affected by milk yield, PFR, main milking time, and AFR. However, stripping yield was negatively correlated with plateau phase and positively correlated with decline phase. Peak flow rate was negatively correlated with main milking time and plateau phase, whereas positive correlations were observed with milk yield, decline phase, and AFR. However, at an udder level, no relationship between PFR and milk yield or between PFR and decline phase was observed (Figure 5a and b). In contrast, PFR and AFR were similarly correlated at a quarter and at an udder level (Figure 5c). The regression coefficient between PFR and AFR was $b = 0.73$ at a quarter level and $b = 0.61$ at an udder level. This means that at a quarter level, an increase of the AFR by 1 unit was associated with an increase in PFR by 1.37 units. At an udder level, a 1-unit increase in AFR was associated with an increase in PFR of 1.61 units. Main milking time was positively correlated with plateau phase and negatively with decline phase. Plateau phase and decline phase were negatively correlated.

Several correlations between teat anatomy and milkability were observed. Teat length was negatively correlated with milk yield, plateau phase, and AFR. In contrast, teat length was positively correlated with stripping yield and decline phase. Teat diameter was positively correlated with PFR, whereas teat canal length was negatively correlated with PFR and AFR. The negative correlation between teat canal length and PFR was observed similarly at a quarter and at an udder level (Figure 5d). Similarly, teat canal length and AFR were negatively correlated at a quarter and an udder level.

Surprisingly, teat anatomy and VO were correlated neither at a quarter level, nor at an udder level (Figure 6a). In contrast, VO was negatively correlated with PFR at an udder and a quarter level (Figure 6b). Furthermore, VO was negatively correlated with decline phase and AFR, but positively correlated with main milking time and plateau phase (Table 4).

DISCUSSION

To our knowledge, this study is the first one that used a combination of approaches to characterize teat anatomy and milkability at a quarter level. The measurements of teat anatomy, teat functionality, and milk flow characteristics were performed using an innovative combination of ultrasonography, vacuum measurement, and continuous milk flow recording. The combination allowed a correlation analysis covering all obtained data.

Figure 4. An exemplary quarter and udder milk flow curve. The peak flow rate (PFR), plateau phase, decline phase, and stripping phase are indicated in one quarter and the udder milk flow profile. The vertical line in each milk flow profile indicates the start and end of the decline phase.

Teat length, teat diameter, teat wall thickness, and teat canal length measurements were similar to those in recent studies (Grindal et al., 1991; Rogers and Spencer 1991; Le Du et al., 1994; Neijenhuis et al., 2001). Earlier investigations reported longer and thicker teats (Andreae, 1958; Loppnow, 1959), indicating changes due to the breeding progress of the last decades. Despite these changes, the variation between

cows and quarters was remarkably high in the present study.

Vacuum needed to open the teat canal was determined by the measurement of VO-S and VO-C, and did not differ between front and rear teats. The value of VO-S corresponds to previous results by Le Du et al. (1994) in a comparable approach. The value of VO-C was substantially lower than VO-S. This corres-

Table 3. Milking characteristics¹ at a quarter level.

	Left front	Right front	Left rear	Right rear
Total yield (kg)	2.81 ± 0.09 ^b	2.47 ± 0.09 ^b	4.02 ± 0.12 ^a	4.10 ± 0.13 ^a
Stripping yield (g)	58 ± 15	70 ± 18	94 ± 15	61 ± 13
Main milking time (min)	4.57 ± 0.15 ^b	4.58 ± 0.16 ^b	5.67 ± 0.18 ^a	5.69 ± 0.19 ^a
Peak flow rate (kg/min)	0.81 ± 0.02 ^{a,b}	0.74 ± 0.02 ^b	0.88 ± 0.02 ^{a,b}	0.89 ± 0.02 ^a
Average flow rate (kg/min)	0.63 ± 0.02 ^b	0.58 ± 0.02 ^b	0.73 ± 0.02 ^a	0.74 ± 0.02 ^a
Plateau phase (%)	50.2 ± 2.0 ^b	51.9 ± 2.3 ^b	63.2 ± 1.9 ^a	60.8 ± 2.0 ^a
Decline phase (%)	33.5 ± 1.8 ^a	31.7 ± 2.2 ^a	23.4 ± 1.6 ^b	22.3 ± 1.6 ^b

^{a,b,c}Means with different superscript letters indicate significant differences within a row ($P < 0.05$).

¹Plateau and decline phase are expressed as relative values of the respective milking time.

ponds to results of Williams and Mein (1987), who showed that the initial force required for the start of the milk flow was substantially higher than the force needed to maintain an already established milk flow. Although the present data correspond to previous reports, it has to be considered that the available literature dealing with VO is based on different methodology. Therefore the comparability of the published data is limited (Williams and Mein, 1987; Le Du et al., 1995; Mayntz et al., 1999). The observed milking characteristics confirm previous investigations at a quarter level (Rothenanger et al., 1995; Wellnitz et al., 1999; Weiss et al., 2003).

Correlations

In the present investigation, no correlations between teat canal length and externally measurable anatomical characteristics like teat length or teat diameter were observed. These results are in contrast to former investigations by Loppnow (1959) and Hebel (1978) who found a positive correlation between teat length and teat canal length. However, Loppnow (1959) and Hebel (1978) performed their measurements on teats of slaughtered cows, whereas in the present study, in vivo measurements by ultrasound were evaluated. Thus, their studies disregarded effects of the tone of teat smooth muscles and intramammary pressure (Lefcourt, 1982; Inderwies et al., 2003b). The observed positive correlation between teat canal length and teat wall thickness is as expected, because the teat canal crosses the teat wall at the teat tip.

Negative correlations between teat length and various milking characteristics, e.g., milk yield, main milking time, plateau phase, and AFR are apparently due to differences between front and rear quarters, because milk yield and PFR were higher in rear than in front quarters, and rear teats were shorter and thicker than front teats. Furthermore, the fact that rear teats were thicker than front teats could explain the positive correlations between teat diameter and PFR, because rear teats had a higher PFR. Indeed, when correlations

within cow were analyzed no significant relationships were observed. The parallel increase of stripping yield and teat length with increasing number of lactations might explain the positive correlation between teat length and stripping yield (Michel and Rausch, 1988; Göft et al., 1994). However, disregarding these apparent correlations between teat anatomy and milking characteristics, there was a negative correlation between teat canal length and PFR, as well as a negative correlation between teat canal length and AFR. These findings correspond to previous reports (Grindal et al., 1991), where the length of the teat canal was shorter in quarters with a high PFR. In summary, these results indicate that externally measurable teat anatomy, i.e., teat length and teat diameter, did not affect important milking characteristics like PFR and AFR.

Surprisingly, teat canal length was not correlated with VO (VO-S nor VO-C), but VO was indeed negatively correlated with PFR and AFR. These findings correspond to investigations by Le Du et al. (1994) and Mayntz et al. (1999). Equal results were observed at a quarter and an udder level. Because the milking vacuum was definitely higher than VO, a correlation between VO and PFR was not to be expected. Furthermore, the resulting teat canal diameter during milk flow, which was not determined in this study, is reported as the most important aspect concerning PFR (Baxter, 1950; Andreae, 1958; Mein et al., 1973; Williams et al., 1986). The present method was designed to measure VO, although no information about intensity and velocity of the observed milk flow and about the teat canal diameter is available by this method, the obtained results reflects information comparable to an approach proposed by Williams and Mein (1980). However, the opening process of the teat canal is caused by tangential and longitudinal forces along the teat canal (Scott and Reitsma, 1978). The present measurement of VO reflects solely the start of the opening of the teat canal. No information about the force that is necessary to open the teat canal to a maximum is available. In previous studies, a relationship between PFR and the adrenergic system has been demon-

Table 4. Pearson's coefficients of correlation¹ between teat anatomy, vacuum needed to open the teat canal, and milk flow. Values above the diagonal show correlations at an udder level and values below the diagonal show correlations at a quarter level.

	Teat length	Teat wall thickness	Teat diameter	Teat canal length	VO-S	VO-C	Milk yield	Stripping yield	Peak flow rate	Main milking time	Plateau phase	Decline phase	Average flow rate
Teat length													
Teat wall thickness	0.03												
Teat diameter	0.13	0.26**											
Teat canal length	0.13	0.50***	0.05										
VO-S ²	-0.05	0.01	0.03	0.08									
VO-C ³	-0.08	-0.02	-0.01	0.10	0.82***								
Milk yield	-0.42***	0.00	0.15	-0.02	0.08	0.00							
Stripping yield	0.19*	0.14	0.13	0.13	0.11	-0.13	0.04						
Peak flow rate	-0.08	-0.12	0.18*	-0.24**	-0.35***	-0.34***	0.34***	0.02					
Main milking time	-0.37***	0.04	0.02	0.14	0.31***	0.23**	0.69***	0.06	-0.33***				
Plateau phase	-0.30**	0.04	-0.15	0.03	0.37***	0.29**	0.44***	-0.23**	-0.32***	0.58***			
Decline phase	0.26**	0.12	0.15	0.02	-0.36***	-0.31***	-0.39***	0.27**	0.22**	-0.45***	-0.94***		
Average flow rate	-0.18*	-0.08	0.15	-0.19*	-0.24**	-0.24**	0.57***	-0.01	0.85***	-0.16	0.02	-0.12	

¹Pearson's coefficients of correlation: *, **, and *** = $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

²VO-S = Start of milk flow during determination of the vacuum needed to open the teat canal.

³VO-C = Cessation of milk flow during determination of the vacuum needed to open the teat canal.

strated (Roets et al., 1989; Wellnitz et al., 2001; Inderwies et al., 2003a). Inderwies et al. (2003b) demonstrated recently that not only the teat canal determines the resulting PFR. Probably, VO reflects the sympathetic tone of the smooth muscles, and the presented method provides information about the adrenergic system of the mammary gland.

In cows with extremely high PFR, the supply of alveolar milk during milking can be crucial for the actual milk flow rate (Bruckmaier et al., 1994; Pfeilsticker et al., 1995) if the maximum milk flow rates, determined by the milk duct system and the teat, are higher than the supply of alveolar milk by the milk ejection reflex. In this case, a short peak with a prolonged decline phase would be visible in the milk flow curve. The present investigation supports this hypothesis, as a positive correlation between PFR and the decline phase was observed at a quarter level.

A close correlation between PFR and AFR was observed at a quarter and an udder level. Interestingly, an increase in AFR was associated with a larger increase of PFR at an udder level than at a quarter level. This difference is because, at a quarter level, the plateau phase (phase of PFR) was more pronounced and therefore resulted in a higher regression coefficient for the relationship between PFR and AFR compared with an udder level. At the udder level, the plateau phase lasted from the start of the plateau phase until the end of the plateau phase in the fastest milking quarter. In contrast, at a quarter level, the plateau phase represents the period where cisternal milk is available (Pfeilsticker et al., 1995; Wellnitz et al. 1999). The increase in PFR in association with an increased AFR is therefore more pronounced at an udder level than at a quarter level. This aspect is of importance with respect to breeding for milkability. With increasing AFR, the PFR will concomitantly increase to a higher extent. To prevent an excessive increase in PFR and therefore an increase in mastitis susceptibility, a control of the PFR besides breeding for increased AFR could be a promising option in breeding programs.

CONCLUSIONS

The teat canal length and the vacuum to open the teat canal were negatively related to peak flow rate and average flow rate at a quarter level. Individual milkability at an udder level is a complex characteristic that is determined by the milkability at a quarter level and the distribution of quarter milk yields. No correlations were present between milkability traits and externally measurable teat characteristics like teat length and teat diameter.

Figure 5. Relationship between peak flow rate, milk yield (a), relative decline phase (b), average flow rate (c), and teat canal length (d) at a quarter and an udder level, respectively. Level of significance and correlation coefficients are indicated in the figures.

Figure 6. Relationship between the vacuum needed to open the teat canal at cessation of milk flow (VO-C), teat canal length (a), and peak flow rate (b) at a quarter and an udder level, respectively. Levels of significance and correlation coefficients are indicated in the figures.

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