Quarter milk flow patterns in dairy cows: factors involved and repeatability

V. Tancin[1,2], A.H. Ipema[2], D. Peskovicova[1], P.H. Hogewerf[2], J. Macuhova[3]

[1]Research Institute of Animal Production, Nitra, Slovak Republic
[2]IMAG, Wageningen, The Netherlands
[3]Institute of Physiology, FML, Technical University Munich, Freising, Germany

ABSTRACT: The objectives of our study were to describe the variation of quarter milk flow parameters and to determine the factors that affect these parameters the most. Additionally, repeatabilities (r^2) of the quarter milk flow traits (duration of milk flow, time to reach peak flow, peak flow rate, and duration of milk flow in single phases – increase, plateau, decline and blind phase) were calculated. Repeatability of total milk yield and milk yield in single phases was calculated, too. The data from 39 Holstein cows, in their first to third lactation and free of clinical mastitis, were used for statistical analysis. A total of 1 656 curves of quarter milk flows were recorded during six consecutive days. At the last evening and morning milking samples of milk from each quarter were collected for determination of somatic cell count (SCC). Peak flow rate, quarter position, time of milking (morning and evening) and SCC significantly affected most of the measured traits. The highest r^2 were for total milk yield and yield of plateau phase 0.53 and 0.50, resp. The lowest r^2 were calculated for the duration of increase phase, and milk yield of the increase and blind phase 0.26, 0.12 and 0.21, resp. Peak flow rate, SCC, time of milking and front-rear position influenced the values of r^2 of traits to various extent.

Keywords: dairy cows; quarter; milk flow; SCC; repeatability

The technical possibilities of industry allow developing new milking machines with partial or full automation of the milking process. Such technical possibilities must build the new milking machines based on the acceptance of the biological requirements of the cow. The acceptance of the biological potentials and limitations of the dairy cows allows us to milk them fast and complete and reduce or exclude any adverse effects on the cows (Tancin and Bruckmaier, 2001).

Flow-controlled systems that are able to change functional parameters according to the current milk flow could improve the milk removal process. However, more efficient control systems require single quarter based milk flow data, due to considerable differences in milk yield and time milk flow patterns between cows and quarters within cows (Marx and Pursel, 1970; Rothschild *et al*., 1980; Mihina *et al*., 1991; Hillerton, 1997; Ipema and Hogewerf, 2002; Tancin *et al*., 2001). Also the recording of the udder milk flow during milking was studied in detail and presented useful and essential information on the course of milking including the efficiency of milk ejection (Bruckmaier and Blum, 1998) and mastitis problems (Naumann *et al*., 1998). However, due to technical limitations only a limited and insufficient analysis of quarter milk flow patterns have been performed. For example, the quarter milk flow parameters could be useful information for automated monitoring of health problems (Tancin *et al*., 2002) and for adequate switch off of the milking units from each individual quarter (Philpot, 1972).

Repeatability of udder milk flow parameters is also important for the genetic evaluation of the milkability (Worle *et al*., 1988; Duda, 1995). Also there is only few information about repeatability of milk flow parameters at the quarter level in literature. Furthermore, repeatability of the milk flow parameters could be an important source of information related to the cow biology, milking machine performance and possible health problems.

The objectives of our study were to describe the variation of quarter milk flow parameters and to determine the factors that affect these parameters the most. Repeatability of the quarter milk flow parameters related to peak flow rate, somatic cell count, time of milking and position of the quarters was examined too.

MATERIAL AND METHODS

Animals and milking parameters

The trial was conducted at the IMAG experimental farm "De Vijf Roeden" in the Netherlands. A total of 39 Holstein cows, in their first to third lactation, were investigated. Cows were in different stages of lactation and free of clinical symptoms of mastitis. The cows were fed *ad libitum* and received additional concentrates according to their milk production levels.

The cows were milked twice daily at 5:30 a.m. and 3:30 p.m. in the 2 × 3 open tandem milking parlour. Each stall in the milking parlour was equipped with four milk receiver jars, the advancing weight of which was recorded each second. The milk weight registrations during a milking are converted to a milk flow rate profile for each individual quarter (Ipema and Hogewerf, 2002). Premilking udder preparation consisted of forestripping, cleaning and drying with a dry paper towel for a period of about 8–10 s per udder. After this short preparation, the cluster was immediately attached. Milking and pulsation vacuum was set at 43 kPa. Pulsation ratio was 65 : 35 at a rate of 60 c/min. The cluster (all four teat cups) was automatically removed 4 s after the whole udder milk flow had decreased below 0.3 kg/min for a period of 12 s.

Quarter milk flows were recorded during 6 consecutive days of the trial. On the last evening and morning milking samples of milk from each quarter were collected for SCC.

Total milk yield (g) is given per one quarter. TMX (s) represents the time to reach peak flow rate. Peak flow rate (g/min) represents the maximum milk flow rate at any time window of 30 s. The increase phase (s) represents the time from attachment until the plateau is reached. Stabile milk flow was considered as duration of plateau phase (s). Decline phase (s) represents reducing of milk flow and lasts from the end of plateau until the moment when the flow for the first time is lower than 0.1 kg/min per quarter. Overmilking – blind phase (s) of the quarter lasts from the end of decline phase until the cluster was automatically removed. The milk flow trait (s) represents the sum of the duration of the increase, plateau and decline phases. Average milk flow (g/min) was calculated as milk yield (g) recorded in the first three phases of milking divided by the duration of milk flow.

Statistical methods

A general linear model with fixed effects was used to identify the main sources of variation for studied traits in preliminary statistical analyses (Table 2 for analysed factor and description). Statistical significance of the effects included in the model was tested by using Fisher's *F*-test. Differences between the levels of the effects were tested by Scheffe multiple range test for studied traits. Some milk flows were excluded due to recording failure, and less total milk yield than 0.6 kg. Therefore in total 1 656 curves of quarter milk flow were used for statistical evaluation (755 milk flows morning, 901 milk flows evening).

Based on the analyses mentioned above, milk flow parameters differed mainly between front and rear position therefore in the following mixed model to estimate coefficient of repeatability for the milk yield and milk flow rate traits the quarter effect was defined as front-rear position only.

$$y = X\beta + Zu + e \qquad (1)$$

where: y = were the measurements for a quarter milk yield and flow traits (duration of milk flow, TMX, peak flow rate, average flow rate, total yield, duration of increase, plateau, decline and blind phase, milk yield of increase, plateau, decline and blind phase)

β = the fixed effects of parity, stage of lactation, peak flow rate, SCC, time of milking, day of milking, front-rear position.

u = random effect of cow, $u \sim N(0, I\,\sigma_c^2)$

e = random error, assuming $e \sim N(0, I\,\sigma_e^2)$

X, Z = incidence matrices for fixed effects and random cow effect, resp.

Cow and error variances were estimated using the REML method (restricted maximum likelihood method) implemented in the SAS statistical software in the procedure MIXED (SAS, 2001) using the single trait mixed models. The estimated variances were used for the estimation of repeatability of studied milk yield and flow rate traits [$r^2 = \sigma_c^2/(\sigma_c^2 + \sigma_e^2)$].

Because the stability of the milk yield and milk flow the traits were of interest in our study, which could be evaluated by repeatability coefficients, the model equations (1) mentioned above were used to estimate repeatability coefficients for different subsets of data. The partial data sets were created according to: (i) peak flow rate (high, middle, or low), (ii) SCC (over and less than 5×10^5 cells/ml), (iii) time of milking (morning or evening), (iv) and front rear position (front and rear quarters).

Following this scheme, respective effects were excluded from the model equation and repeatability coefficients were estimated for partial data sets. In Tables data are presented as least square means (lsmeans) and standard error, except the data in Table 1 presented as mean and standard deviation.

RESULTS

Basic statistics of the data set is presented in Table 1.

All studied traits were highly influenced ($P < 0.001$) by the effect of peak flow rate, SCC, time of milking and quarter position (Table 2), therefore only these data are shown in the Table 3.

The effect of parity, stage of lactation and day of trial influenced only some of the studied traits (Table 2). The cows on their first lactation had significantly lower production (2 188 ± 183 g) and the duration of milk flow (281 ± 18 s) per quarter than other cows (2 832 ± 90 g, 330 ± 11 s, resp.). The milk yield and duration of milk flow significantly decreased from 2 972 ± 226 g and 356 ± 23 s (1st stage, resp.) to 1 814 ± 210 g and 256 ± 21 s (4th stage of lactation, resp.) (Table 2). Effect of parity and stage had similar effect on TMx, duration and yield of plateau phase as on milk yield or the duration of milk flow (Table 2). The days of trial significantly influenced the total yield, duration of increase and blind phase, yield of increase and blind phases (Table 2). Data did not show any increase or decrease tendency of lsmeans in the course of the trial. Variation of lsmeans of quarter milk yield within trial was between 2 432 g to 2 576 g.

From the most important differences in peak flow rate (Table 3) we can mention the shorter duration of milk flow, higher milk yield on one side and longer duration of decline and blind phase for the

Table 1. Basic statistics of the data set (n = 1 656)

Traits	Mean	S.D.	Min	Max
Milk flow (s)	301.3	95.2	143	755
TMx (s)	183.5	85.6	64	711
Peak flow rate (g/min)	895.8	289.3	339	1 668
Aaverage flow rate (g/min)	563.0	172.4	227	1 096
Yield (g)	2 788.0	962.8	778	6 371
Duration of phases				
increase (s)	79.4	20.9	18	270
plateau (s)	157.2	96.0	30	598
decline (s)	64.8	49.8	2	431
blind (s)	58.9	66.5	0	489
Milk yield of phases				
increase (g)	398.2	219.4	15	1 726
plateau (g)	1 948.4	913.2	355	5 720
decline (g)	395.6	275.3	6	2 244
blind (g)	45.8	58.9	0	727

Table 2. Results of analyses of variance for milk yield and milk flow traits (statistical significance of the Fisher's *F*-test). Analysed factors: two levels of parities (1st – cows on their first lactation, 2nd – cows on their second and third lactation), four levels of stages of lactation (1st stage: 1st to 3rd month; 2nd stage: 4th to 6th month; 3rd stage: 7th to 9th month; and 4th stage: 10th to 11th month of lactation), three levels of peak flow rate (high – more than 1 kg/min, middle – between 0.6–1 kg/min, low – less than 0.6 kg/min), two levels of somatic cell count – SCC (over and less than 5 × 10^5 cells/ml), time of milking (morning and evening), days of trial (six continuous days of data recording) and four quarter positions (front and rear by left and right side)

Traits	Parity	Stage of lactation	Peak flow rate	SCC	Time of milking	Days of trial	Quarter positions
Milk flow	++	++	+++	++	+++	–	+++
TMX	+	++	+++	+++	+++	–	+++
Peak flow rate	–	–	+++	–	–	–	+++
Average flow rate	–	–	+++	+++	+++	–	+++
Yield	++	+++	+++	+++	+++	++	+++
Duration of phases							
increase	–	–	+++	+	+++	++	+++
plateau	+	++	+++	+++	+++	–	+++
decline	–	–	+++	+++	–	–	–
blind	–	–	+++	++	++	+	+++
Milk yield of phases							
increase	–	–	+++	+	+++	+	+++
plateau	++	+++	+++	+++	+++	–	+++
decline	–	–	+++	+++	–	–	+++
blind	–	–	+++	–	–	+++	+++

TMx – time to reach peak flow
+ $P < 0.05$; ++ $P < 0.01$; +++ $P < 0.001$

quarters with high peak flow rate when compared with the low ones.

There was a significantly longer duration of increase, decline, and blind phase and lower milk yield in quarters with high SCC (Table 3). However, there were no differences in peak flow rate of two SCC groups of quarters.

The time of milkings (morning, evening) parameter did not show any effect on peak flow, duration of decline phase, and yield of decline and blind phases (Table 3).

The quarter position significantly influenced all traits except the duration of decline phase (Table 3). Front quarters were overmilked (blind phase) longer than rear ones but there were no differences between front and rear quarters in the duration of decline phases. There was no clear difference between front and rear quarters in peak flow rate but front quarters significantly differed from rear ones in average flow rate and milk yield (Table 3). In generally, the differences among quarters were related to front-rear positions.

The estimated coefficients of repeatability for the traits are presented in Table 4. The highest repeatabilities were found for total milk yield and yield of plateau phase 0.53 and 0.50, resp. The lowest repeatabilities were calculated for the duration of increase phase, and milk yield of the increase and decline phases, 0.26, 0.12 and 0.21, resp. Within the evaluated factors – peak flow rate, SCC, and front-rear position – the values of repeatability of traits differed mostly. Repeatabilities of measured parameters within milkings factor had similar values for morning and evening milking. The lowest r^2 was found in the duration and milk yield of the increase

Table 3. Least squares means for quarter milk flow and yield traits according estimated factors

Traits		Peak flow rate			SCC		Time of milking		Quarter position			
		high	low	middle	over	less	morning	evening	right front	left front	right rear	left rear
n		678	306	672	239	1 417	755	901	413	413	415	415
Milk flow (s)	lsmean	268^{a}	357^{b}	299^{c}	300^{a}	315^{b}	331^{a}	283^{b}	282^{a}	267^{b}	343^{c}	338^{c}
	Std Error	11.9	12.2	11.6	12.5	11.3	11.6	11.6	11.7	11.8	11.7	11.7
TMx (s)	lsmean	155^{a}	220^{b}	175^{c}	170^{a}	196^{b}	199^{a}	168^{b}	172^{a}	156^{b}	204^{c}	200^{c}
	Std Error	10.5	11.0	10.2	10.9	9.6	10.1	10.1	10.4	10.5	10.3	10.2
Peak flow rate (g/min)	lsmean	$1\,120^{a}$	561^{b}	824^{c}	836	834	830	840	792^{a}	835^{b}	813^{a}	834^{b}
	Std Error	22.8	23.8	21.9	20.8	20.8	21.7	21.6	22.3	22.4	21.9	21.9
Average flow rate (g/min)	lsmean	639^{a}	354^{b}	494^{c}	549^{a}	467^{b}	513^{a}	479^{b}	459^{a}	480^{b}	511^{c}	532^{d}
	Std Error	18.1	18.2	17.6	17.8	17.5	17.4	17.5	17.9	18.0	17.8	17.8
Yield (g)	lsmean	$2\,907^{a}$	$2\,062^{b}$	$2\,518^{c}$	$2\,327^{a}$	$2\,665^{b}$	$2\,791^{a}$	$2\,201^{b}$	$2\,094^{a}$	$2\,119^{a}$	$2\,862^{b}$	$2\,908^{b}$
	Std Error	113	116	113	116	110	112	111	113	113	112	112
Duration of phases increase												
increase	lsmean	78^{a}	87^{b}	80^{a}	84^{a}	80^{b}	83^{a}	80^{b}	82^{a}	78^{b}	84^{c}	83^{ac}
	Std Error	2.8	3.0	2.7	3.0	2.6	2.7	2.7	2.8	2.8	2.7	2.7
plateau (s)	lsmean	102^{a}	210^{b}	142^{c}	131^{a}	172^{b}	173^{a}	129^{b}	129^{a}	116^{b}	182^{c}	178^{c}
	Std Error	11.9	11.3	11.3	11.9	11.1	11.3	11.2	11.4	11.5	11.4	11.3
decline (s)	lsmean	88^{a}	59^{b}	77^{c}	86^{a}	64^{b}	74	74	72	74	77	75
	Std Error	7.8	8.2	7.7	8.2	7.5	7.7	7.7	7.8	7.9	7.7	7.7
blind (s)	lsmean	96^{a}	19^{b}	72^{c}	69^{a}	56^{b}	66^{a}	59^{b}	87^{a}	102^{b}	28^{c}	33^{c}
	Std Error	11.6	11.9	11.4	11.9	11.1	11.3	11.3	11.5	11.5	11.4	11.4
Milk yield of phases increase												
increase	lsmean	510^{a}	277^{b}	370^{c}	404^{a}	367^{b}	421^{a}	350^{b}	359^{a}	375^{ab}	389^{b}	417^{c}
	Std Error	19.6	20.8	18.5	22.1	16.5	18.1	18.1	19.5	19.8	18.9	18.9
plateau (g)	lsmean	$1\,777^{a}$	$1\,476^{b}$	$1\,673^{a}$	$1\,389^{a}$	$1\,895^{b}$	$1\,902^{a}$	$1\,382^{b}$	$1\,228^{a}$	$1\,254^{a}$	$2\,013^{b}$	$2\,013^{b}$
	Std Error	116	112	110	120	118	115	119	116	116	115	115
decline (g)	lsmean	559^{a}	279^{b}	422^{c}	485^{a}	356^{b}	419	421	359^{a}	420^{b}	433^{b}	443^{b}
	Std Error	38.2	39.6	36.1	39.1	34.5	36.2	35.1	37.8	37.9	37.2	37.3
blind (g)	lsmean	68^{a}	24^{b}	54^{c}	52	46	52	48	62^{a}	71^{b}	27^{c}	34^{d}
	Std Error	7.4	7.9	7.1	7.9	7.6	7.2	7.0	7.3	7.4	7.2	7.2

For explanation see table 1

a,b,c,d – within one factor values without a common superscript letter were significantly different at $P < 0.05$

Table 4. Estimated coefficients of repeatability for milk yield and milk flow traits for different subsets of data (see Table 2, only front-rear position of quarters were used in model)

Traits	r^2 by peak flow rate			r^2 by somatic cell count		r^2 by time of milking		r^2 by front rear position		r^2 in whole
	high	low	middle	over	less	morning	evening	front	rear	data set
Milk flow	0.48	0.68	0.55	0.77	0.50	0.63	0.60	0.55	0.61	0.46
TMX	0.38	0.36	0.34	0.76	0.34	0.58	0.58	0.33	0.52	0.32
Peak flow rate	0.36	0.42	0.35	0.61	0.33	0.62	0.54	0.41	0.30	0.30
Average flow rate	0.59	0.48	0.41	0.46	0.41	0.66	0.65	0.43	0.54	0.40
Yield	0.67	0.41	0.77	0.86	0.55	0.88	0.89	0.69	0.76	0.53
Duration of phases										
increase	0.35	0.19	0.24	0	0.28	0.27	0.43	0.29	0.28	0.26
plateau	0.53	0.62	0.59	0.84	0.49	0.59	0.62	0.60	0.62	0.46
decline	0.45	0.45	0.49	0.11	0.43	0.56	0.56	0.47	0.54	0.40
blind	0.65	0.39	0.50	0.88	0.56	0.47	0.26	0.60	0.43	0.48
Milk yield of phases										
increase	0.09	0.11	0.22	0.36	0.12	0.34	0.24	0.18	0.09	0.12
plateau	0.63	0.50	0.69	0.83	0.53	0.67	0.64	0.65	0.71	0.50
decline	0.46	0.39	0.44	0.30	0.37	0.61	0.54	0.46	0.54	0.35
blind	0.16	0.30	0.25	0.76	0.33	0.26	0.22	0.32	0.15	0.21

phase in all calculated factors. Important values of r^2 were calculated in a group with high SCC as compared to other groups.

DISCUSSION

The effect of parity and stage of lactation on milk yield and average flow was similar as published Rothschild *et al.* (1980) except for peak flow. We did not find the negative effect of stage of lactation on peak flow though milk yield decreased. However, as compared with our data, Rothschild *et al.* (1980) had data from the same cows tested once during each stage of lactation or parity. Therefore it is not possible to make a clear conclusion from our data in relation to stage and parity.

The differences in milk flow between morning and evening milking are related to the milk yield in our experiment. It is consequence of unequal duration of the time between morning and evening milking. Though we had significant difference in milk production, there were no effects of morning and evening milking on peak flow as it was noted in another study also (Wagner and Ruegg, 2002).

A significant effect of the day of trial was related to the milk yield and duration and yield of increase and blind phases only, though the same procedure was performed before milking. The effect of the day on the duration and yield of increase phases could be explained by the cow response to shorter preparation for milking. Furthermore, the lowest repeatability of the duration and yield of the increase phase within the studied factors were calculated in our trial. Repeatability of the basal intramammary pressure was not very high until the milk ejection occurred (Pfeilsticker *et al.*, 1995).

There are several evidences indicating possible positive relationship between the duration of the decline phase of milk flow and the health status at udder (Naumann *et al.*, 1998) or quarter level (Tancin *et al.*, 2001, 2002). It is also known that cows with a high peak flow rate are more sensitive to mastitis (Grindal and Hillerton, 1991). The decline phase of the udder milk flow pattern is largely caused by overmilking of earlier milked out quarters. Overmilking is a high risk for udder health (Natzke *et al*., 1982) although no correlation between the duration of overmilking and SCC was found (Wellnitz *et al*., 1999). On the other hand, the decline phase of the quarter milk flow could indicate the equilibrium between filling of udder cistern with alveolar milk and emptying the teat cistern by machine. Our statistic model revealed the longest duration of blind phase and high repeatability of mentioned data of both groups of quarters with high peak flow rate and high SCC. Also both mentioned groups of quarters showed longer duration of decline phase.

On the base of our results we could also speculate whether quarters with high peak flow rate are more sensitive to mastitis due to the longer overmilking or duration of decline phase or both of them. Front quarters were overmilked two or three times longer than rear ones in our trial, but we have found significantly higher SCC in rear quarters (Tancin *et al.,* 2002). But results of this experiment showed significantly longer duration of blind phase of quarters with high peak flow rate and high SCC. Probably overmilking of quarters with high peak flow rate could contribute to their higher sensitivity to mastitis because of the teat end conditions in relation to the bacterial penetration and growth. The overmilking is one of the negative factors influencing the teat end conditions (Hamann, 1994).

Our data of quarter milk flow traits are similar to those published at the quarter level by Rothschild *et al*. (1980) or front-rear level by Hogewerf and Ipema (2000) or by Tancin *et al*. (2002). However, we could not clearly demonstrate the difference between front and rear quarters in peak flow rate as it was also confirmed in other work (Wellnitz *et al*., 1999). Perhaps because of other factors involved in the statistical model the effect of front-rear quarter position has little effect on peak flow rate.

On the base of all data together, the highest repeatabilities were calculated for total milk yield and yield of plateau phase and the lowest r^2 for the duration of increase phase, and milk yield of the increase and blind phases. High repeatability (r^2 = 0.83) of peak flow rate was reported by Pfeilsticker *et al.* (1995). In another work repeatability for average and maximum flow rate at the quarter level was 0.60 and 0.63, resp., but r^2 for milk yield of plateau phase was 0.1 only (Rothschild *et al*., 1980).

Conclusion. In this experiment the quarter milk flow and yield parameters were not always influenced by the studied factors. Peak flow rate significantly influenced all measured traits only. Peak flow rate, SCC, time of milking and front-rear position influenced the values of r^2 of traits to various extent. Our data contribute to the knowledge concerning the further development of machine milking equipment based more on the acceptance of biology of the quarters to milk cows faster and keep udder health.

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Corresponding Author

Doc. Ing. Vladimir Tancin, CSc., Research Institute of Animal Production, Hlohovska 2, SK-949 92 Nitra, Slovak Republic
Tel. +421 376 546 153, e-mail: tancin@vuzv.sk