Analysis of milking characteristics in New Zealand dairy cows

J. P. Edwards,^{*1} J. G. Jago,^{*} and N. Lopez-Villalobos[†]

^{*}DairyNZ, Private Bag 3221, Hamilton 3240, New Zealand

[†]Institute of Veterinary, Animal and Biomedical Sciences, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand

ABSTRACT

The objective of this study was to describe the variation in milking characteristics, and factors associated with these traits, in grazing dairy cows milked without premilking stimulation. Milk yield, duration, and average and maximum milk flow rate data were collected from 38 farms in New Zealand at 2 time points (spring and autumn) during the 2010 to 2011 season. Subsequently, a second data set, allowing the generation of daily milk flow profiles, was collected from 2 farms in the 2011 to 2012 season. Corresponding animal data, such as breed, date of birth, and ancestry information, were extracted from the New Zealand Dairy Industry Good Animal Database (New Zealand Animal Evaluation Ltd., Hamilton, New Zealand). Residual milking duration (deviation from the regression line of milk yield on milking duration) was calculated, allowing the identification of fast-milking cows independent of milk yield. Variance components for the milking characteristics traits were estimated using an animal linear mixed model. The average milk yield was 10 kg/milking and the average milking duration was 360 s. The average milk flow rate was 1.8 kg/min and maximum milk flow 3.3 kg/min, with 44% of milk flow curves being classified as bimodal. Primiparous animals exhibited different milk flow profiles, with a lower maximum flow, than multiparous animals, possibly due to differences in cisternal capacity. Residual milking duration was shortest (−10 s) in mid-lactation (121–180 d) and was 13 s longer for Jersey compared with Friesian cows; however, it was 19 s shorter when adjusted for energy content. Residual milking duration had a negligible genetic correlation (−0.07) with milk yield, indicating that selection for cows with shorter residual milking duration should have a negligible effect on milk yield. A heritability of 0.27 indicated that residual milking duration could be valuable as part of a breeding program. Knowledge of the distribution of milking durations for a given milk yield allows farmers to choose appropriate

cluster-on time when using a maximum milking time strategy to improve milking efficiency.

Key words: milk flow profile, milking efficiency, milking speed

INTRODUCTION

The milking facility represents a significant proportion of farm capital investment in pasture-based dairy systems. In addition, a recent study has highlighted that some farmers may have overcapitalized by building parlors that are larger than necessary (Edwards et al., 2013a). Milk harvesting is a labor-intensive task, requiring up to 57% of time annually in pastoral dairy systems (Taylor et al., 2009), which may increase as herd sizes expand (DairyNZ, 2012). Consequently, interest in milking efficiency has been renewed (Edwards et al., 2013c). Improving milking efficiency could increase throughput in existing parlors or, when constructing a new parlor, allow a similar level of throughput to that achieved previously with fewer clusters.

Parlor milking efficiency is strongly influenced by the milking duration of individual cows. Accordingly, research has focused on strategies to reduce the milking duration of cows, such as milking to a predetermined time (Clarke et al., 2004; Jago et al., 2010a,b). In herringbone parlors, the row time is determined by the slowest milking cow, and in rotary parlors the number of bails occupied by cows requiring multiple rotations to complete milking is determined by cow milking duration (Edwards et al., 2012), both influencing parlor throughput. As a longer cow milking duration increases labor costs, it is not surprising that milking speed has been linked to farm profitability and has been included as part of animal breeding programs (Sivarajasingam et al., 1984; Boettcher et al., 1998).

Cow milking duration is determined by milk yield and milk flow rate, which varies during different phases of a milking (Tančin et al., 2006). So, when selecting for cows with shorter milking durations, care is required to ensure that milk yield is not negatively affected, as milking duration has been reported to be positively associated with milk yield (Sandrucci et al., 2007; Gray et al., 2011; Samoré et al., 2011). Likewise, faster-milking

Received May 21, 2013.

Accepted September 24, 2013.

¹Corresponding author: Paul.Edwards@dairynz.co.nz

cows have been linked to poorer udder health (Brown et al., 1986; Grindal and Hillerton, 1991; Tančin et al., 2007). Consequently, Berry et al. (2013a) proposed the use of 2 new traits: residual milking duration and residual milking duration including SCC, calculated using the residual of milking duration regressed on milk yield (and SCC). Subjective scores of milking speed are heritable (Meyer and Burnside, 1987; Sewalem et al., 2011). However, in order for these new traits to be useful as part of a breeding program, their genetic correlations and heritabilities require evaluation.

Milk flow curves can be used to determine where differences in broad measures of milking characteristics, such as milking duration, average flow, and maximum flow, may be occurring (Edwards et al., 2013b). Milking characteristics can vary depending on factors such as parity, breed, and stage of lactation (McCarthy et al., 2007; Sandrucci et al., 2007; Walsh et al., 2007). Furthermore, the use of premilking stimulation, present in previous studies, has not been widespread in many pasture-based systems for 40 yr, after work by Phillips (1987) demonstrated that it was no longer required to maximize milk production. However, the effect of a lack of premilking stimulation on milking characteristics and milk flow curves has not been thoroughly explored on animals not accustomed to premilking routines. European studies suggest that cows milked without premilking stimulation are more likely to have bimodal milk flow curves, reducing average milk flow rate and potentially affecting udder health (Bruckmaier and Blum, 1996; Sandrucci et al., 2007). The response to premilking stimulation of cows in New Zealand pastoral systems is reported to be variable (Edwards et al., 2013c); thus, the identification of cows that do not display bimodal milk curves when milked without premilking stimulation may be advantageous.

The objective of this study was to describe the phenotypic variation and genetic correlations in milking characteristics of a strain of cows not accustomed to premilking stimulation. A secondary objective was to determine the relationship between milk yield and expected milking duration. Such information can be used to identify fast-milking animals and assist in making informed decisions on culling, appropriate milking routines, and parlor operation (milking to a predetermined time).

MATERIALS AND METHODS

Data Collection

Participating farms were selected for their ability to record milking data and all were equipped with electronic identification of cows, electronic milk meters,

automatic cluster removers (ACR), and herd management software that recorded individual milking events. Farms were located throughout the dairying regions of New Zealand. All had rotary parlors and 4 different milking equipment manufacturers were represented. A data set was collected from approximately 10 milking sessions at 2 time points: in spring (September–November 2010) and in autumn (February–April 2011). A total of 38 farms were used, resulting in milking data from 24,056 spring-calving (July–September) cows. All farms conducted at least 1 herd test during the season where milk composition and SCC data were collected.

The herd management software on each farm was programmed to record similar fields. The variables recorded included cow number, birth identification, electronic identification number, date of birth, milking date, identification (**ID**) time, bail number, milk yield (kg), milking duration (s), average flow (kg/min), maximum flow (kg/min), calving date, and DIM.

Animal data for the 38 farms were extracted from the New Zealand Dairy Industry Good Animal Database [New Zealand Animal Evaluation Ltd. (NZAEL), Hamilton, New Zealand]. Fields extracted included owner participant code, map reference, herd number, animal key, birth ID, birth date, ancestry information, and proportion (in 16ths) of Holstein-Friesian (**F**), Ayrshire, Brown Swiss, Friesian, Guernsey, Jersey (**J**), and milking Shorthorn breed. Additionally, herd test information, such as fat and protein percentages and SCC, were extracted. This data set was merged by cow with the milking data collected on farm. All data manipulations were carried out using SAS (version 9.3; SAS Institute Inc., Cary, NC).

A second data set (detailed data set) was collected from 2 of the farms between September 2011 and May 2012. The dairies were equipped with Metatron S21 milk meters (GEA Farm Technologies GmbH, Bönen, Germany) at every bail. At each milking session, the herd management software (DairyPlan C21; GEA Farm Technologies GmbH) was set up to record cow number, registration number, milking date, milking time, milk yield, milking duration (cluster-on to cluster-off), average milk flow rate (from initiation of milk flow to cluster removal), maximum milk flow rate, time from cluster attachment to maximum milk flow rate, milk yield in the first 2 min, and time from maximum milk flow rate to end of milking. The average milk flow rate was recorded in 15-s intervals up to 4 min, 30-s intervals between 4 and 7 min, and 60-s intervals from 7 to 10 min. Animal data from the relevant time period were extracted from the New Zealand Dairy Industry Good Animal Database (NZAEL) for the 2 herds and matched to corresponding animals from the milking data. Fields extracted included cow number, birth ID,

animal key, date of birth, and calving date, which allowed the calculation of DIM. Ancestry information and herd test data, including volume, fat and protein percentages, and SCC, were also extracted.

Statistical Analysis

Calculations of breed proportions and coefficients of breed heterozygosity were completed for each cow. The breed composition of each cow was described in terms of the proportion of F, J, and other (**O**) breeds, and was calculated for individual animals using the following formula: $\alpha_i^p = (\alpha_i^s + \alpha_i^d)/2$, where α_i^p is the proportion of genes from breed *i* in the progeny, α_i^s is the proportion of breed *i* in the sire, and α_i^d is the proportion of breed *i* in the dam.

Coefficients of specific heterosis and recombination were calculated between any pair of the F, J, and O breeds using the following identities (Dickerson, 1973): $h_{ij} = \alpha_i^s \alpha_j^d + \alpha_j^s \alpha_i^d$ and $r_{ij} = \alpha_i^s \alpha_j^s + \alpha_j^d \alpha_i^d$, where h_{ij} and r_{ij} are the coefficients of expected heterosis and recombination between fractions of breeds *i* and *j* in the progeny, α_i^s and α_j^s are proportions of breeds *i* and *j* in the sire, respectively, and α_i^d and α_j^d are proportions of breed *i* and *j* in the dam, respectively. Deviation from the median calving date of the herd was calculated for each cow.

Dependent variables analyzed in the 38-farm data set were milk yield, ECM yield, milk duration, average flow, residual milking duration (**RMD**), energy-corrected RMD (**ECRMD**), residual milk flow (**RMF**), and RMD adjusted by milk yield and SCC (**RMDS**). Following Berry et al. (2013a), RMD is the residual value from the regression line of milk duration on milk yield, ECRMD is the residual value from the regression line of milk duration on ECM yield, RMF is the residual value from the regression line of average flow on milk yield, and RMDS is the residual value after fitting a linear regression model of milk duration on milk yield and SCC. The ECM yield was calculated using the formula $ECM = \text{milk yield} \times (383 \times \text{fat percentage} + 242 \times \text{protein percentage} + 783.2)/3,140$ (Beever and Doyle, 2007), derived from Tyrrell and Reid (1965).

Dependent variables analyzed in the detailed data set were milk yield; milking duration; average flow; maximum flow; time to maximum flow; yield in the first 2 min; percentage of yield in the first 2 min; decline duration; bimodality of the flow curve; RMD; RMF; RMDS; yield of milk, fat, and protein; percentage of fat and protein; and SCC calculated as $\log_2$ SCC. A flow curve was defined as bimodal if during the first 75 s, the milk flow rate decreased by more than 0.2 kg/min from one

15-s time interval to the next, the milk flow rate during the second and third 15-s time intervals after either remained the same or increased, and the milk flow rate thereafter was greater than zero. Bimodality of the milk flow curve was considered a trait with a binomial distribution. All variables were analyzed using mixed models in ASReml software (Gilmour et al., 2009), with a model that included cow as a random effect to account for repeated measures on the same animal, and the fixed effects of farm ($n = 38$ or $n = 2$), parity (1, 2, 3, or 4+), stage of lactation (d 1–60, 61–120, 121–180, 181–240, or 240–300), session (a.m. or p.m.), and interaction between parity and stage of lactation. The dependent variable, bimodality of the flow curve, was analyzed with the same model but after a logit transformation (Gilmour et al., 1985). Deviation from the median herd calving date, proportion of J, proportion of O breeds, and heterosis and recombination coefficients for $F \times J$, $F \times O$, and $J \times O$ were included in the model as continuous variables. Proportion of F was not included in the model to avoid linear dependencies and was used as a base for comparison. Two-way and 3-way interactions between parity, stage of lactation, and milking session were also tested for association with the dependent variable. Least squares means for the fixed effects that were considered as classes were obtained at the average values for the other terms in the model. Estimates of variance components required for the calculation of heritabilities using the 38-farm data set were obtained using ASReml software (Gilmour et al., 2009), with the same model described above plus the random effect of animal. This was extended as a bivariate repeatability animal model for the estimation of genetic and phenotypic correlations. The pedigree file included 3 generations of ancestry information.

For the detailed data set, milk flow rates at different intervals after attaching clusters were analyzed with a mixed model with repeated measures on the same cow, using the same model as described above but including the fixed effect of time for each a.m. or p.m. session. Using the Akaike information criterion, a completely general (unstructured) covariance was determined as the most appropriate residual covariance structure for repeated measures over time within each cow and session. Marginal means of average milk flow rate at 7, 22, 37, 52, 67, 82, 112, 127, 142, 157, 172, 187, 202, 217, 232, 255, 285, 315, 345, 375, 405, 450, 510, and 570 s were obtained for bimodality, each parity, session, and stage of lactation. As the milk flow rate at each point was an average of all cows (i.e., with maximum flow rate occurring at different times) the apparent maximum flow rate, at whichever time point it occurred, was less than the mean maximum flow rate recorded by the system.

Table 1. Descriptive statistics of milking data collected from 38 herds

Milking characteristic	Mean	SD
Milk yield (kg/milking)	10.06	4.32
Milking duration (s)	360.22	125.82
Average flow (kg/min)	1.75	0.61
Maximum flow (kg/min)	3.27	1.28
Residual milking duration (s)	0.0	105.81
Residual milk flow (kg/min)	0.0	0.45
RMDS ¹ (s)	0.0	113.15
Log ₂ SCC	6.19	1.76

¹Residual milking duration including SCC.

Estimation of Milking Time

The relationship between milk yield, categorized to the nearest kilogram, and milking duration when 1, 80, and 99% of cows had completed milking was obtained using a univariate analysis to obtain means and quartiles of milking duration at different milk yields from the 38-farm data set.

RESULTS

38-Farm Data Set

The descriptive statistics of the data set collected from 38 farms (24,056 cows) at 2 time points are presented in Table 1. The mean milking duration was 360 s, with a standard deviation of 126 s. The summary statistics by parity are reported in Table 2 and show that milk yield, milking duration, and average and maximum flow rate increased with age. Trends observed in RMD, RMF, and RMDS were less clear but appeared to be poorer (i.e., lower RMD and RMDS, greater RMF) for older cows (parity 4+). Breed differences, relative to the F breed, are displayed in Table 3 and indicate that J have poorer RMD, RMF, and RMDS in comparison with other breeds, except when corrected for energy content. Genetic and phenotypic correlations and heritabilities of the milking characteristics are reported in Table 4.

The heritabilities ranged from 0.15 to 0.31. Milk yield had medium genetic correlations with milking duration, average milk flow, and maximum milk flow (0.23 to 0.31) and close to zero genetic correlation with RMD, RMF, and RMDS. Milking duration had high negative correlations with average milk flow, maximum milk flow, and RMF but strong positive genetic correlations with RMD and RMDS.

Detailed Data Set

Detailed milking characteristics of 1,555 cows (621,116 milk flow curves) by lactation stage in periods of 60 d are reported in Table 5. Milk yield, milking duration, time to maximum flow, yield in the first 2 min, and decline duration all decreased as lactation advanced. Average and maximum milk flow peaked at 61 to 120 d and declined thereafter. The percentage of total milk yield harvested in the first 2 min and the percentage of bimodal milk flow curves increased with stage of lactation, except for the latter in the final 60-d period. Residual milking duration, RMF, and RMDS all peaked in the period 121 to 180 d. The mean percentage of bimodal flow curves was $44 \pm 0.6\%$. Bimodal milk flow curves had the following phenotypic correlations: milk yield: 0.12, milking duration: -0.14, average milk flow: 0.27, maximum milk flow: 0.32, yield in the first 2 min: 0.16, RMD: -0.25, and RMDS: -0.26. All were statistically significant ($P < 0.05$). Bimodality was not correlated with SCC ($P = 0.96$). The average milk flow curves of bimodal and non-bimodal milkings is shown in Figure 1. Similarly, the average milk flow curves by parity are shown in Figure 2, where the flow curves of primiparous animals were not bimodal and reached a lower maximum milk flow. The RMD at the morning milking was 6.9 s compared with -4.2 s for the afternoon milking ($P < 0.05$). The RMF was -0.06 kg/min for the morning milking compared with 0.01 kg/min for the afternoon milking ($P < 0.001$). However,

Table 2. Least squares means of each parity (1, 2, 3, and 4+) using data collected from 38 herds at 2 time points (peak and late lactation); the averages of both time points are presented

Milking characteristic	Age class								P-value
	Parity 1	SE	Parity 2	SE	Parity 3	SE	Parity 4+	SE	
Number of animals	2,693		4,328		4,690		12,345		
Milk yield (kg/milking)	7.23 ^a	0.08	8.00 ^b	0.06	9.08 ^c	0.07	9.83 ^d	0.05	<0.0001
Milking duration (s)	311.6 ^a	2.90	320.4 ^b	2.38	335.1 ^c	2.53	356.7 ^d	1.68	<0.0001
Average flow (kg/min)	1.52 ^a	0.02	1.57 ^a	0.01	1.69 ^b	0.01	1.72 ^b	0.01	<0.0001
Maximum flow (kg/min)	2.69 ^a	0.03	2.85 ^b	0.03	3.12 ^c	0.03	3.20 ^c	0.02	<0.0001
Residual milking duration (s)	-4.69 ^{ab}	2.87	-4.86 ^{ab}	2.36	-7.64 ^a	2.54	0.41 ^b	1.68	0.028
Residual milk flow (kg/min)	0.056 ^a	0.01	0.026 ^a	0.01	0.038 ^a	0.01	-0.005 ^b	0.01	<0.0001
RMDS ¹ (s)	-6.80 ^{ab}	1.97	-12.91 ^b	1.97	-10.89 ^b	1.97	-1.84 ^a	1.97	0.002

^{a-d}Means within a row without a common superscript are significantly different ($P < 0.05$).

¹Residual milking duration including SCC.

Table 3. Regression coefficients comparing breed [Jersey (J) and heterosis (Het)] relative to the Holstein-Friesian (F) breed using data collected from 38 herds

Milking characteristic	Breed effect					
	J	SE	<i>P</i> -value	Het F × J	SE	<i>P</i> -value
Milk yield (kg/milking)	−2.42	0.08	<0.0001	0.41	0.04	<0.0001
ECM yield (kg)	−0.52	0.04	<0.0001	0.58	0.03	<0.0001
Milking duration (s)	−25.56	3.73	<0.0001	8.60	2.18	<0.0001
Average flow (kg/min)	−0.31	0.02	<0.0001	0.04	0.01	<0.0001
Maximum flow (kg/min)	−0.52	0.04	<0.0001	0.06	0.02	<0.0001
Residual milking duration (s)	12.99	3.66	<0.0001	2.70	2.13	0.102
ECRMD ¹ (s)	−18.81	1.48	<0.0001	−1.88	1.15	0.102
Residual milk flow (kg/min)	−0.08	0.02	<0.0001	0.00	0.01	0.421
RMDS ² (s)	0.68	7.56	0.464	6.07	5.26	0.124

¹Energy-corrected residual milking duration.²Residual milking duration including SCC.

the RMDS was −4.2 s for the morning milking and −1.0 s for the afternoon milking ($P < 0.001$). The percentage of milk harvested in the first 2 min increased from 34% at morning milking to 41% in the afternoon ($P < 0.001$). The average milk flow curve for each 60-d period of lactation is presented in Figure 3 and shows the curve becoming more bimodal as the lactation progressed.

Estimation of Milking Time

The relationship between milk yield and milking duration is reported in Figure 4, and shows the variation in milking duration for a given milk yield. The equation for the line where 80% of cows had completed milking was milking duration (min) = $0.35 \times \text{milk yield (kg)} + 3.30$.

DISCUSSION

The objective of this study was to describe and quantify the variation in the milking characteristics of New Zealand dairy cows, which are not accustomed to premilking stimulation. Notable differences in milking characteristics were detected in the present study between breed, parity, and stage of lactation. Knowledge of the variation in milking characteristics between animals and its genetic links may be exploited to improve milking efficiency and, consequently, the profitability of dairy farms. The results clearly show that variation between animals exists, despite adjusting for differences in milk yield (residual milking duration), which has been proposed as a measure for the selection of animals with efficient milking characteristics (Berry et al., 2013a).

Breed differences were detected between F and J animals, with J averaging a lower milk yield, lower average and maximum milk flow, and shorter milking duration,

but taking an additional 13 s to milk out when adjusted for milk yield (Table 3), a result consistent with Berry et al. (2013a). Conversely, crossbred animals had a greater milk yield and longer milking duration than F animals; however, no differences were observed in RMD or residual average flow. Thus, based on these measures J animals had poorer milking characteristics. However, J animals have a higher percentage of milk solids, so where payment systems are based on fat and protein yields, their milk has more value per unit volume. Consequently, after adjusting for energy content, J animals yielded only 0.5 kg less than F (compared with 2.4 kg for uncorrected yield), while maintaining a 25-s shorter milking duration, resulting in an ECRMD of 19 s less than that of F. A reduction of 19 s in milking duration could equate to a 5% increase in the number of cows milked per hour in a rotary dairy (Edwards et al., 2012). Thus, in industries with a composition-based payment system, J animals appear to have superior milking efficiency, demonstrating that RMD alone may not be the most appropriate measure for the selection of milking speed.

Primiparous animals appeared to have a different average milk flow curve compared with older animals, with a lower initial milk flow rate, and a lower maximum milk flow rate (Figure 2). Differences in the milk flow curves of primiparous animals has been reported previously by Hillerton (2010), who suggested that this was likely due to cisternal capacity. Multiparous animals tend to have larger cisterns that contain a greater proportion of total milk compared with primiparous animals (Bruckmaier et al., 1994). Milk held in the cistern can be rapidly removed, as evidenced by the greater initial increase in milk flow rate relative to primiparous animals (Figure 2). However, as milk is extracted, the flow rate declines, creating a bimodal flow curve, before the milk ejection reflex occurs and milk is transferred from the alveolar compartment to the cistern, increas-

Table 4. Heritabilities (on the diagonal), genetic (below the diagonal), and phenotypic (above the diagonal) correlations between the milking characteristic traits using data collected from 38 herds (SE of the correlations are in parentheses)

Trait	MY	MD	AMF	MMF	RMD	RMF	RMDS
Milk yield (MY)	0.15 (0.01)						
Milking duration (MD)	0.23 (0.05)	0.27 (0.04)	0.55 (0.003)	0.24 (0.004)	-0.13 (0.005)	0.09 (0.005)	-0.08 (0.010)
Average milk flow rate (AMF)	0.39 (0.04)	-0.79 (0.02)	-0.56 (0.004)	-0.49 (0.004)	0.92 (0.001)	-0.82 (0.002)	0.93 (0.001)
Maximum milk flow rate (MMF)	0.31 (0.04)	-0.81 (0.02)	0.23 (0.01)	0.64 (0.003)	-0.80 (0.002)	0.88 (0.001)	-0.79 (0.004)
Residual milking duration (RMD)	-0.07 (0.05)	0.95 (0.00)	0.95 (0.01)	0.31 (0.02)	-0.61 (0.003)	0.64 (0.003)	-0.61 (0.006)
Residual milking flow (RMF)	0.00 (0.05)	-0.96 (0.01)	-0.93 (0.01)	-0.93 (0.01)	0.27 (0.02)	-0.88 (0.001)	0.99 (0.000)
Residual milking duration including SCC (RMDS)	-0.00 (0.08)	0.95 (0.01)	0.92 (0.01)	0.91 (0.01)	-0.98 (0.00)	0.28 (0.02)	-0.87 (0.002)
			-0.88 (0.02)	-0.91 (0.03)	0.99 (0.00)	-0.97 (0.01)	0.31 (0.04)

ing the milk flow rate again. In comparison, the cistern of primiparous animals remains full throughout milking due to its relatively constrained capacity, so milk is continuously resupplied from the alveoli, which combined with a smaller teat than that of older animals, results in a more uniform curve and lower maximum milk flow rate (Hillerton, 2010). However, although this result is interesting, the age structure of the herd would be difficult to modify on the grounds of milking efficiency.

Stage of lactation had a strong influence on milking characteristics. Similar to parity, attempting to modify the stage of lactation for milking efficiency is not practical; however, examining the changes in detailed milking characteristics and milk flow curves at different stages of lactation may help to understand underlying reasons for differences in RMD. Milk yield and milking duration were greatest in the stage 0 to 60 d and declined thereafter. However, average and maximum milk flow were greatest during the stage 61 to 120 d, whereas RMD and RMDS were lowest and RMF greatest during the stage 121 to 180 d. The peak in milking efficiency during mid lactation (121–180 d) was likely a result of changes within the mammary gland. As stage of lactation increased, Knight et al. (1994) reported less resistance to the movement of milk from the alveolar compartment to the cistern, indicating that the cistern changes to accommodate more milk. Similarly, Dewhurst and Knight (1993) reported an increase in the cisternal fraction (proportion of the total milk held in the cistern) as lactation stage increased. This is supported by the results of the present study where the percentage of milk harvested in the first 2 min, typically cisternal milk, increased as lactation progressed (Table 5). However, some studies have reported a decline in cisternal fraction over lactation (Pfeilsticker et al., 1996), possibly due to factors such as breed and milking interval. Cisternal milk can be rapidly removed from the udder, so a greater amount of milk held in this compartment likely results in a greater baseline pressure (Pfeilsticker et al., 1995). This hypothesis was also used to explain how cows milked with increased automatic cluster remover thresholds achieved greater average milk flow rates (Edwards et al., 2013b). Conversely, less milk held is in the alveolar compartment as lactation progresses, resulting in less milk being transferred to the cistern for the same level of myoepithelial cell contraction, which causes delayed milk ejection in late lactation (Bruckmaier and Hilger, 2001). Thus, the trade-off between the positive influence of an increasing proportion of cisternal milk and negative influence of an increase in time to milk ejection may explain why the lowest RMD and RMDS values occurred in mid lactation and, consequently, provides a possible physiological basis for differences in RMD.

Table 5. Least squares means of milking characteristics at each stage of lactation (periods of 60 d) using milk meter data collected daily and milk composition data collected at 4 herd tests from 2 farms

Milking characteristic	Stage of lactation (d)										<i>P</i> -value
	0–60	SE	61–120	SE	121–180	SE	181–240	SE	241–300	SE	
Milk yield (kg/milking)	12.07 ^a	0.05	11.02 ^b	0.05	9.76 ^c	0.05	8.92 ^d	0.05	7.45 ^e	0.05	<0.0001
Milking duration (s)	416.2 ^a	2.47	378.4 ^b	2.47	347.0 ^c	2.47	335.1 ^d	2.47	316.9 ^e	2.47	<0.0001
Average flow (kg/min)	2.05 ^b	0.01	2.08 ^a	0.01	2.01 ^c	0.01	1.89 ^d	0.01	1.68 ^e	0.01	<0.0001
Maximum flow (kg/min)	3.41 ^c	0.03	3.47 ^a	0.03	3.46 ^b	0.03	3.34 ^d	0.03	3.04 ^e	0.03	<0.0001
Time to maximum flow (s)	164.4 ^a	1.26	151.4 ^b	1.26	136.3 ^c	1.26	129.6 ^d	1.26	123.2 ^e	1.27	<0.0001
Yield to 2 min (kg)	3.43 ^a	0.03	3.34 ^b	0.03	3.22 ^c	0.03	3.03 ^d	0.03	2.63 ^e	0.03	<0.0001
Percent of yield to 2 min	33.2 ^e	0.32	34.7 ^d	0.32	37.7 ^c	0.32	38.9 ^b	0.32	40.4 ^a	0.33	<0.0001
Decline duration (s)	126.9 ^a	1.22	106.4 ^b	1.22	99.8 ^c	1.22	100.1 ^c	1.22	96.0 ^d	1.23	<0.0001
Predicted probability for bimodality	0.381 ^e	0.005	0.456 ^c	0.006	0.467 ^b	0.006	0.473 ^a	0.006	0.418 ^d	0.006	<0.0001
Residual milking duration (s)	19.3 ^a	2.40	−0.77 ^b	2.40	−10.4 ^d	2.40	−7.71 ^c	2.40	−0.51 ^b	2.41	<0.0001
Residual milk flow (kg/min)	−0.09 ^e	0.01	0.04 ^b	0.01	0.07 ^a	0.01	0.02 ^c	0.01	−0.07 ^d	0.01	<0.0001
RMDS ¹ (s)	17.7 ^a	2.81	−8.03 ^c	2.92	−22.3 ^d	3.10	−11.8 ^c	3.03	2.36 ^b	3.58	0.0152
Herd test yield (kg)	11.2 ^a	0.08	9.99 ^b	0.09	8.91 ^c	0.10	7.97 ^d	0.09	6.55 ^e	0.13	<0.0001
Fat (%)	4.09 ^e	0.02	4.23 ^d	0.02	4.93 ^c	0.02	5.29 ^b	0.02	5.74 ^a	0.03	0.001
Protein (%)	3.63 ^e	0.01	3.78 ^d	0.01	3.84 ^d	0.01	4.26 ^b	0.01	4.53 ^a	0.03	0.0057
Fat yield (kg)	0.44 ^a	0.003	0.41 ^b	0.003	0.44 ^a	0.004	0.41 ^b	0.004	0.35 ^c	0.005	<0.0001
Protein yield (kg)	0.40 ^a	0.003	0.37 ^b	0.003	0.34 ^c	0.003	0.34 ^c	0.003	0.29 ^d	0.004	<0.0001
Log ₂ SCC	5.97 ^e	0.04	6.33 ^d	0.04	6.74 ^c	0.04	7.13 ^b	0.04	7.44 ^a	0.05	<0.0001
Back-transformed SCC (×1,000)	63		80		107		140		174		

^{a–e}Means within a row without a common superscript are significantly different ($P < 0.05$).¹Residual milking duration including SCC.

Figure 1. Average milk flow curves for bimodal (double line) and non-bimodal (single solid line) milkings using milk meter data collected daily from 2 farms.

Clearly, variations in milking characteristics between animals exist; however, to be useful for animal breeding genetic correlations and heritabilities, these variations require examination. The estimate of heritability in this study (0.27) is consistent with previous heritability estimates for electronically recorded milking duration, which vary from 0.11 to 0.30 (Zwald et al., 2005; Gray et al., 2011; Samoré et al., 2011; Berry et al., 2013b). Residual milking characteristics (RMD, RMF, and RMDS) can be useful for evaluating animals or groups of animals for their milking speed, irrespective of milk yield. The moderate values of heritability (0.27–0.31) for residual milking characteristics were similar to the 0.18 to 0.22 reported by Berry et al. (2013b) and indicate that these measures could be used in a selective breeding program to improve milking efficiency. The results of the current study indicate that this can be achieved without affecting milk yield because the genetic correlations of milk yield with RMD, RMF, and RMDS

Figure 3. Average milk flow curves for each 60-d stage of lactation (double line = 1–60; dotted line = 61–120; dashed line = 121–180; single solid line = 181–240; open dashed line = 241–300) using milk meter data collected daily from 2 farms.

were almost zero. Alternately, genetic correlations suggest that selection for average and maximum milk flow could achieve a similar improvement in milking speed. However, average and maximum flow had positive genetic correlations with milk yield, indicating that a consequence of selecting for improved milking speed using these traits would be greater milk yield. Increasing milk yield may have undesirable implications for an already balanced farm system (e.g., increasing herd energy requirements). Furthermore, European research has indicated that selection for average milk flow may lead to poorer udder health (Bahr et al., 1995; Gäde et al., 2007). Similarly, Berry et al. (2013b) reported a genetic correlation of -0.30 between both RMD and RMDS and SCS. Somatic cell count data in the present study were only available as a composite of morning and afternoon and, therefore, were not suitable for

Figure 2. Average milk flow curves for 4 parities (double line = parity 1; dotted line = parity 2; dashed line = parity 3; single solid line = parity 4+) using milk meter data collected daily from 2 farms.

Figure 4. Relationship between milk yield (categorized to nearest kilogram) and milking duration when 1% (double line), mean (dotted line), 80% (dashed line), and 99% (single solid line) of cows have completed milking, using data collected at 2 time points (spring and autumn) from 38 farms.

the calculation of phenotypic and genetic correlations. Consequently, residual milking characteristics appear to provide an effective way to improve milking speed without affecting milk yield and could be implemented in a breeding program; however, further studies examining the relationship with SCC are required.

A unique feature of this study was that no stimulation was applied to cows before milking, as is standard practice on New Zealand dairy farms (Phillips, 1987). Cows milked without prior stimulation are more likely to display bimodal milk profiles (Bruckmaier and Blum, 1996); correspondingly, the mean number of bimodal flow curves in the current study was 44% higher than in other studies where premilking stimulation was practiced (Sandrucci et al., 2007; Samoré et al., 2011; Berry et al., 2013a). As discussed previously, it appears that milking efficiency may be related to a greater proportion of cisternal milk, a conclusion supported by Edwards et al. (2013b); however, this may result in a greater number of bimodal milk profiles (Edwards et al., 2013c). For example, the predicted proportion of bimodal profiles increased with lactation stage, along with the percentage of milk harvested in the first 2 min (Table 5). Similar trends were observed comparing morning and afternoon milkings. Bimodality has been considered a negative trait in Europe (Bruckmaier and Blum, 1996; Tamburini et al., 2010), due to the transient milking of teats during the period of low milk flow. However, any cow with cisternal milk and delayed milk ejection will likely display a bimodal milk flow profile, which does not necessarily result in a period of blind milking. Figure 1 indicates that, on average, under New Zealand conditions, the stimulatory effect of the milking machine resulted in the milk ejection reflex occurring before the cistern emptying, so the milk flow rate of the bimodal profiles remained above zero. Correspondingly, bimodality was not correlated with SCC. Thus, the lack of premilking stimulation should not be a concern for New Zealand dairy farmers, as bimodal milk flow curves do not appear to negatively affect milking efficiency or SCC, a result supported by Edwards et al., (2013b,c).

Knowledge of the variation in milking characteristics within a herd can also be used to improve milking efficiency without compromising milk yield or quality through the use of a maximum milking time strategy (Clarke et al., 2004; Jago et al., 2010a,b). The key criterion of this strategy is to remove clusters after a set time. The time is selected so the slowest 20% of cows have their milking truncated; thus, the appropriate time varies according to the distribution of cow milking durations within a herd and will change depending on factors such as stage of lactation. To be applied practically on farm, the method of selecting the maximum

milking time must be simple. Milk yield (Figure 4) is the logical choice, as it explains a large amount of variation in milking duration, can be easily calculated from milk-collection receipts, and consequently is the method advocated by researchers in New Zealand and Australia (CowTime, 2003; DairyNZ, 2013). However, Jago et al. (2010b) reported that current guidelines may result in more than 20% of milkings being truncated. Figure 4 can be used to select an appropriate maximum milking time for a given yield and highlights how significant improvements to average cow milking duration can be achieved by truncating the slowest cows. For example, if waiting for all cows to milk out in a herringbone parlor, the row time for a herd yielding 10 kg/milking would be at least 12 min, compared with only 7 min if truncating the slowest 20% of cows. This is one of few published large data sets (24,056 cows) using animals in a pasture-based production system and, thus, can provide operators with a degree of confidence that they are choosing the appropriate maximum milking time for their individual situation.

CONCLUSIONS

Breed differences in milking characteristics exist, with F and crossbred animals having a shorter RMD than J animals. However, J had a shorter RMD when corrected for milk composition. The milking characteristics of primiparous animals were different to those of multiparous animals, likely due to differences in cisternal capacity. Milking characteristics also changed as lactation progressed, with RMD shortest in mid lactation. Bimodality was not correlated with poorer milking efficiency or SCC; thus, the lack of premilking stimulation should not be a concern for New Zealand dairy farmers. Finally, residual milking characteristics are heritable and, therefore, could have application for selecting fast-milking animals independent of milk yield but further investigation into the genetic relationship with SCC is required.

ACKNOWLEDGMENTS

This study was part of a program of research funded by New Zealand dairy farmers through DairyNZ Inc. (Hamilton, New Zealand). The authors acknowledge the assistance of DeLaval International AB (Tumba, Sweden), GEA Farm Technologies GmbH (Bönen, Germany), Milfos International Ltd. (Hamilton, New Zealand), and Waikato Milking Systems NZ Ltd. (Hamilton, New Zealand) in identifying potential farms, and the contribution of the farmers who provided benchmark data.

REFERENCES

- Bahr, T., R. Preisinger, and E. Kalm. 1995. Investigations on somatic cell count and milkability of dairy cows 2nd communication. Part 2: Genetic parameters of milkability traits. *Züchtungskunde* 67:105–116.
- Beever, D. E., and P. T. Doyle. 2007. Feed conversion efficiency as a key determinant of dairy herd performance: A review. *Aust. J. Exp. Agric.* 47:645–657. <http://dx.doi.org/10.1071/ea06048>.
- Berry, D. P., B. Coughlan, B. Enright, S. Coughlan, and M. Burke. 2013a. Factors associated with milking characteristics in dairy cows. *J. Dairy Sci.* 96:5943–5953. <http://dx.doi.org/10.3168/jds.2012-6162>.
- Berry, D. P., J. Coyne, B. Coughlan, M. Burke, J. McCarthy, B. Enright, A. R. Cromie, and S. McParland. 2013b. Genetics of milking characteristics in dairy cows. *Animal* 7:1750–1758. <http://dx.doi.org/10.1017/S1751731113001511>.
- Boettcher, P. J., J. C. M. Dekkers, and B. W. Kolstad. 1998. Development of an udder health index for sire selection based on somatic cell score, udder conformation, and milking speed. *J. Dairy Sci.* 81:1157–1168. [http://dx.doi.org/10.3168/jds.S0022-0302\(98\)75678-4](http://dx.doi.org/10.3168/jds.S0022-0302(98)75678-4).
- Brown, C. A., S. J. Rischette, and L. H. Schultz. 1986. Relationship of milking rate to somatic cell count. *J. Dairy Sci.* 69:850–854. [http://dx.doi.org/10.3168/jds.S0022-0302\(86\)80475-1](http://dx.doi.org/10.3168/jds.S0022-0302(86)80475-1).
- Bruckmaier, R. M., and J. W. Blum. 1996. Simultaneous recording of oxytocin release, milk ejection and milk flow during milking of dairy cows with and without prestimulation. *J. Dairy Res.* 63:201–208. <http://dx.doi.org/10.1017/S0022029900031708>.
- Bruckmaier, R. M., and M. Hilger. 2001. Milk ejection in dairy cows at different degrees of udder filling. *J. Dairy Res.* 68:369–376. <http://dx.doi.org/10.1017/S0022029901005015>.
- Bruckmaier, R. M., E. Rothenanger, and J. W. Blum. 1994. Measurement of mammary-gland cistern size and determination of the cisternal milk fraction in dairy-cows. *Milchwissenschaft* 49:543–546.
- Clarke, T., E. M. Cuthbertson, R. K. Greenall, M. C. Hannah, E. Jongman, and D. Shoemith. 2004. Milking regimes to shorten milking duration. *J. Dairy Res.* 71:419–426. <http://dx.doi.org/10.1017/s0022029904000421>.
- CowTime. 2003. Shorter milking secrets. Accessed June 30, 2011. http://www.cowtime.com.au/Main.asp?_=Shorter%20Milking%20Secrets.
- DairyNZ. 2012. New Zealand dairy statistics 2011–12. Accessed Sep. 3, 2013. <http://www.dairynz.co.nz/file/fileid/45159>.
- DairyNZ. 2013. Applying Max T info sheet. Accessed Sep. 3, 2013. http://www.milksmart.co.nz/CDF_Resources/Download/Index/79097.
- Dewhurst, R. J., and C. H. Knight. 1993. An investigation of the changes in sites of milk storage in the bovine udder over two lactation cycles. *Anim. Prod.* 57:379–384.
- Dickerson, G. E. 1973. Inbreeding and heterosis in animals. Pages 54–77 in *Proceedings of the Animal Breeding and Genetics Symposium in Honor of Dr. J. L. Lush*. American Society of Animal Science and American Dairy Science Association, Blacksburg, VA.
- Edwards, J. P., J. G. Jago, and N. Lopez-Villalobos. 2013a. Large rotary dairies achieve high cow throughput but are not more labour efficient than medium sized rotaries. *Anim. Prod. Sci.* 53:573–579. <http://dx.doi.org/10.1071/AN12312>.
- Edwards, J. P., J. G. Jago, and N. Lopez-Villalobos. 2013b. Milking efficiency can be improved by increasing automatic cluster remover thresholds to grazing dairy cows without applying pre-milking stimulation. *J. Dairy Sci.* 96:3766–3773. <http://dx.doi.org/10.3168/jds.2012-6394>.
- Edwards, J. P., J. G. Jago, and N. Lopez-Villalobos. 2013c. Short-term application of prestimulation and increased automatic cluster remover threshold affect milking characteristics of grazing dairy cows in late lactation. *J. Dairy Sci.* 96:1886–1893. <http://dx.doi.org/10.3168/jds.2012-6191>.
- Edwards, J. P., N. Lopez-Villalobos, and J. G. Jago. 2012. Increasing platform speed and the percentage of cows completing a second rotation improves throughput in rotary dairies. *Anim. Prod. Sci.* 52:969–973. <http://dx.doi.org/10.1071/AN12071>.
- Gäde, S., E. Stamer, J. Bennewitz, W. Junge, and E. Kalm. 2007. Genetic parameters for serial, automatically recorded milkability and its relationship to udder, health in dairy cattle. *Animal* 1:787–796. <http://dx.doi.org/10.1017/S1751731107000092>.
- Gilmour, A. R., R. D. Anderson, and A. L. Rae. 1985. The analysis of binomial data by a generalized linear model. *Biometrika* 72:593–599. <http://dx.doi.org/10.1093/biomet/72.3.593>.
- Gilmour, A. R., B. J. Gogel, B. R. Cullis, and R. Thompson. 2009. *ASReml User Guide*. Release 3.0. VSN International Ltd., Hemel Hempstead, UK.
- Gray, K. A., F. Vacirca, A. Bagnato, A. B. Samoré, A. Rossoni, and C. Maltecca. 2011. Genetic evaluations for measures of the milk-flow curve in the Italian Brown Swiss population. *J. Dairy Sci.* 94:960–970. <http://dx.doi.org/10.3168/jds.2009-2759>.
- Grindal, R. J., and J. E. Hillerton. 1991. Influence of milk flow rate on new intramammary infection in dairy cows. *J. Dairy Res.* 58:263–268. <http://dx.doi.org/10.1017/S0022029900029848>.
- Hillerton, J. E. 2010. Control of peak flow rate of milk from the cow's teat. Pages 449–453 in *Mastitis Research Into Practice: Proceedings of the 5th IDF Mastitis Conference*. J. E. Hillerton, ed. VetLearn, Christchurch, New Zealand.
- Jago, J. G., J. K. Burke, and J. H. Williamson. 2010a. Effect of automatic cluster remover settings on production, udder health, and milking duration. *J. Dairy Sci.* 93:2541–2549. <http://dx.doi.org/10.3168/jds.2009-2949>.
- Jago, J. G., J. E. McGowan, and J. H. Williamson. 2010b. Effect of setting a maximum milking time, from peak lactation, on production, milking time and udder health. *N. Z. Vet. J.* 58:246–252. <http://dx.doi.org/10.1080/00480169.2010.69298>.
- Knight, C. H., D. Hirst, and R. J. Dewhurst. 1994. Milk accumulation and distribution in the bovine udder during the interval between milkings. *J. Dairy Res.* 61:167–177. <http://dx.doi.org/10.1017/S0022029900028181>.
- McCarthy, S., D. P. Berry, P. Dillon, M. Rath, and B. Horan. 2007. Effect of strain of Holstein-Friesian and feed system on udder health and milking characteristics. *Livest. Sci.* 107:19–28. <http://dx.doi.org/10.1016/j.livsci.2006.08.014>.
- Meyer, K., and E. B. Burnside. 1987. Scope for a subjective assessment of milking speed. *J. Dairy Sci.* 70:1061–1068. [http://dx.doi.org/10.3168/jds.S0022-0302\(87\)80112-1](http://dx.doi.org/10.3168/jds.S0022-0302(87)80112-1).
- Pfeilsticker, H. U., R. M. Bruckmaier, and J. W. Blum. 1996. Cisternal milk in the dairy cow during lactation and after preceding teat stimulation. *J. Dairy Res.* 63:509–515. <http://dx.doi.org/10.1017/S0022029900032040>.
- Pfeilsticker, H. U., R. M. Bruckmaier, and J. W. Blum. 1995. Interruption of machine milking in dairy cows: Effects on intramammary pressure and milking characteristics. *J. Dairy Res.* 62:559–566. <http://dx.doi.org/10.1017/S0022029900031289>.
- Phillips, D. S. M. 1987. Studies on pre-milking preparation 10. Long-term change in yield response to pre-milking preparation. *N. Z. J. Agric. Res.* 30:317–323. <http://dx.doi.org/10.1080/00288233.1987.10421890>.
- Samoré, A. B., S. I. Román-Ponce, F. Vacirca, E. Frigo, F. Canavesi, A. Bagnato, and C. Maltecca. 2011. Bimodality and the genetics of milk flow traits in the Italian Holstein-Friesian breed. *J. Dairy Sci.* 94:4081–4089. <http://dx.doi.org/10.3168/jds.2010-3611>.
- Sandrucci, A., A. Tamburini, L. Bava, and M. Zucali. 2007. Factors affecting milk flow traits in dairy cows: Results of a field study. *J. Dairy Sci.* 90:1159–1167. [http://dx.doi.org/10.3168/jds.S0022-0302\(07\)71602-8](http://dx.doi.org/10.3168/jds.S0022-0302(07)71602-8).
- Sewale, A., F. Miglior, and G. J. Kistemaker. 2011. Short communication: Genetic parameters of milking temperament and milking speed in Canadian Holsteins. *J. Dairy Sci.* 94:512–516. <http://dx.doi.org/10.3168/jds.2010-3479>.
- Sivarajasingam, S., E. B. Burnside, J. W. Wilton, W. C. Pfeiffer, and D. G. Grieve. 1984. Ranking dairy sires by a linear-programming dairy farm model. *J. Dairy Sci.* 67:3015–3024. [http://dx.doi.org/10.3168/jds.S0022-0302\(84\)81667-7](http://dx.doi.org/10.3168/jds.S0022-0302(84)81667-7).

- Tamburini, A., L. Bava, R. Piccinini, A. Zeconi, M. Zucali, and A. Sandrucci. 2010. Milk emission and udder health status in primiparous dairy cows during lactation. *J. Dairy Res.* 77:13–19. <http://dx.doi.org/10.1017/S0022029909990240>.
- Tančin, V., A. H. Ipema, and P. Hogewerf. 2007. Interaction of somatic cell count and quarter milk flow patterns. *J. Dairy Sci.* 90:2223–2228. <http://dx.doi.org/10.3168/jds.2006-666>.
- Tančin, V., B. Ipema, P. Hogewerf, and J. Mačuhová. 2006. Sources of variation in milk flow characteristics at udder and quarter levels. *J. Dairy Sci.* 89:978–988. [http://dx.doi.org/10.3168/jds.S0022-0302\(06\)72163-4](http://dx.doi.org/10.3168/jds.S0022-0302(06)72163-4).
- Taylor, G., L. van der Sande, and R. Douglas. 2009. Smarter not harder: Improving labour productivity in the primary sector. Accessed Sep. 3, 2013. <http://maxa.maf.govt.nz/sff/about-projects/search/05-028/technical-report.pdf>.
- Tyrrell, H. F., and J. T. Reid. 1965. Prediction of the energy value of cow's milk. *J. Dairy Sci.* 48:1215–1223. [http://dx.doi.org/10.3168/jds.S0022-0302\(65\)88430-2](http://dx.doi.org/10.3168/jds.S0022-0302(65)88430-2).
- Walsh, S., F. Buckley, D. P. Berry, M. Rath, K. Pierce, N. Byrne, and P. Dillon. 2007. Effects of breed, feeding system, and parity on udder health and milking characteristics. *J. Dairy Sci.* 90:5767–5779. <http://dx.doi.org/10.3168/jds.2007-0389>.
- Zwald, N. R., K. A. Weigel, Y. M. Chang, R. D. Welper, and J. S. Clay. 2005. Genetic evaluation of dairy sires for milking duration using electronically recorded milking times of their daughters. *J. Dairy Sci.* 88:1192–1198. [http://dx.doi.org/10.3168/jds.S0022-0302\(05\)72785-5](http://dx.doi.org/10.3168/jds.S0022-0302(05)72785-5).