Persistency and lactation curves modelled using nonlinear random regression in dairy cows milked once a day

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Abstract

Modelling lactation curves of dairy cows is important for improved feed management and breeding decisions. The objectives of this study were to compare measures of lactation persistency obtained from the modelling of lactation curves for daily yields of milk, fat and protein using a nonlinear random regression model in dairy cows milked once a day under grazing conditions. A total of 1,955 monthly herd-test records of milk, fat and protein from 55 Holstein-Friesian (F), 64 Jersey (J), and 123 F×J crossbreds of different lactations were used to obtain lactation curves for each cow using a random regression model with the Wood function. Three measures of persistency were calculated based on ratios of yields and compared with persistency calculated based on parameters of the Wood function. Jersey cows in lactation 3 had the greatest persistency for all persistency measures. In first-lactation cows, there were no significant breed differences in persistency. Persistency measures were strongly correlated with each other ($r \geq 0.97$; $P<0.001$). The conclusion from this study is that parameters of the lactation curve (peak yield, day of peak and persistency) can be precisely estimated using the random regression model with the Wood function.

Keywords: modelling; lactation curve; persistency; once-a-day milking

Introduction

A lactation curve illustrates the pattern of daily milk production during lactation in dairy cows (Wood 1967). A typical lactation curve of milk production can be divided into three phases: an increasing phase between calving and peak yield, a maintaining phase of peak yield and a decreasing phase after the peak (Gengler 1996). Lactation persistency is usually defined as the ability of the cow to maintain a consistent level of milk production after peak yield (Gengler 1996; Wood 1967). A cow is more persistent if her lactation curve is flatter after peak yield, than a cow with the same total yield but with a lactation curve that rapidly decreases after peak yield (Gengler 1996; Macciotta et al. 2011; Wood 1967). Knowledge of the shape of the lactation curve is useful to define feeding and breeding strategies.

A once-a-day milking system (OAD) has been adopted by about 8% of New Zealand dairy farmers for a range of reasons, including reduced farm costs, lifestyle improvement for the farmers and health and welfare improvement for cows (Clark et al. 2006; Edwards 2018). However, production losses of milk volume were reported in OAD compared to twice-a-day (TAD) milking systems (Clark et al. 2006; Hickson et al. 2006; Lembeye et al. 2016), ranging from 21 to 31% in whole lactation studies in New Zealand. Furthermore, cows milked OAD had lower peak yield and fewer days in milk than did cows milked TAD (Clark et al. 2006; Hickson et al. 2006), indicating that improving persistency is the main option to reduce production losses in OAD milking systems. Therefore, selection based on persistency in cows milked OAD would be important to ensure a good transition from TAD to OAD milking.

Many studies have reported the modelling of lactation curves using nonlinear models (Wood 1967; Dijkstra et al. 2010; Piccardi et al. 2017). These studies focused on the modelling of the lactation curve for predicting daily milk yield of individual cows based on about 8 to 10 test-day records. Since 1980, the attention of modelling lactation curves has gradually transferred from modelling the lactation curve for better feed management to modelling the lactation curve for genetic evaluation using random linear regression (Jakobsen et al. 2002; Jamrozik & Schaeffer 1997). A random regression model (RRM) describes the lactation curve of the population of cows (fixed regression coefficients) and the deviations (random regression coefficients) from the fixed regression for each cow. The RRM is more flexible when fitting lactation curves and allows variation among individuals' lactation curves, along with the prediction of daily yields of cows with a limited number of herd-test records, provided that a covariance matrix between the estimates of regression coefficients for any linear mathematical function is available.

However, few studies have explored the use of RRM with nonlinear mathematical functions to model lactation curves and predict total milk yields when cows have a lower (two or three) number of herd-tests. Piccardi et al. (2017) fitted phenotypic lactation curves for milk yield using RRM with three nonlinear functions (Wood, Milkbot and diphasic) and suggested that the Wood function had the best performance to predict lactation traits in the RRM. The objectives of the present study were: a) to model the lactation curves at the phenotypic level for daily yields of milk, fat and protein using RRM with the Wood function in dairy cows milked OAD; b) to compare lactation curves and persistency in Holstein-Friesian (F), Jersey (J) and crossbred (FJ) cows of different parities and investigate the correlations between different persistency measures.

Materials and methods

Data

The data set included 1,955 monthly herd-test records for milk yield (MY), fat yield (FY) and protein yield (PY) obtained from 242 cows milked OAD at Massey University Dairy 1 during the 2018-19 season. There were 55 Holstein Friesian (F), 64 Jersey (J), and 123 F×J crossbred cows with 201 herd-test records from first parity lactations and 420 records from second parity lactations. All the rest were records from third lactation or later lactations which were considered together.

Feeding system and cow management

All cows had access to fresh perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) pasture but the diet composition differed during the production season. In September and December, cows had 100% fresh perennial ryegrass and white clover pasture. Mixtures of plantain (*Plantago lanceolata*) and chicory (*Cichorium intybus*) were offered in October, November and February, accounting for 13%, 33% and 23% of the dry matter intake, respectively. Turnips (*Brassica campestris ssp. rapifera*) were offered in January at 63% of the dry matter intake. From February to April, due to severe pasture shortage, pasture silage was fed directly on the paddock at a percentage of 34%, 67% and 14%, of the daily feed allowance, respectively. Similarly, in August and April, maize (*Zea mays*) silage was offered at 25% and 32% of the dry matter intake, respectively.

Cows were milked OAD at 6:30 AM. Milk yield, and percentages of fat and protein were determined on samples using a Fossomatic FT120 (Foss Electric, Hillerød, Denmark) during routine herd-testing occurred monthly from August to April. Daily yields of fat (FY) and protein (PY) were obtained by multiplying MY by the respective percentages of fat and protein. Calving was from 8 July to 2 October 2018 and all cows were dried off before May 2019.

Lactation curves

Lactation curves for the population and each cow were modelled with RRM based on the Wood function (Wood 1967) using the NLMIXED procedure of SAS version 9.4 (SAS Institute Inc.), which was represented as,

$$y_{it} = (At^{B}e^{Ct}) + (a_i t^{b_i} e^{c_i t}) + e_{it}$$

where y_{it} is the milk yield of cow (i) at day (t), parameter A, B and C are the fixed regression coefficients for the population, parameter a_i, b_i and c_i, are the random regression coefficients expressed as deviations from the population for each cow, and e_{it} is the random residual error. The estimation of ai, bi and ci depends on the estimation of the (co)variance matrix **W** of random regression coefficients

$$\mathbf{W}=\begin{bmatrix} \sigma_a^2 & \sigma_{ab} & \sigma_{ac} \\ \sigma_{ab} & \sigma_b^2 & \sigma_{bc} \\ \sigma_{ac} & \sigma_{bc} & \sigma_c^2 \end{bmatrix}$$

Lactation parameters and persistency

Total yield, peak yield and day at peak were obtained using the predicted daily yields for each cow using the predicted daily yields. Three different measures of persistency (P1, P2, and P3) were calculated for each cow based on the ratio of predicted yields:

$$P1 = \frac{\text{Lactation yield from day 181 to 270}}{\text{Lactation yield from day 1 to 90}} \times 100$$

$$P2 = \frac{\text{Lactation yield from day 121 to 180}}{\text{Lactation yield from day 1 to 60}} \times 100$$

$$P3 = \frac{\text{Total laction yield}}{\text{Peak yield} \times 270} \times 100$$

Persistency (P_w) was measured based on the parameters of the Wood function (Wood 1967) as follows:

$$P_w = -(b+1)\ 1n\,(-c)$$

where ln is the natural logarithm, and a, b and c are the estimates of the Wood function for each cow.

Statistical analysis

Estimates of random regression coefficients for each cow obtained from the Wood function, and measures of persistency, peak yield, day at peak and total yields for MY, FY and PY were analysed with a linear model with the MIXED procedure of SAS version 9.4 (SAS Institute Inc.). The linear model was the following:

$$y_{jki} = \mu + G_j + L_k + GL_{jk} + \beta_1\, k_{jki} + e_{jki}$$

where y_{jki} is the dependent variable measured in cow i, μ is the population mean; G_j is the fixed effect of breed j; L_k is the fixed effect of lactation number k; $GL_{jk}$is the fixed effect of interaction between breed j and lactation number k; β_1 is the regression coefficient of the dependent variable on deviation from median herd calving date of cow i; e_{jki} is the residual random error associated to the observation y_{jki}. Least-squares means and standard error of the means for the fixed effects were obtained and used for multiple mean comparisons using the Fisher's Least Significant Difference as implemented in the LSMEANS option of the MIXED procedure. Significant differences between means were declared at $P<0.05$.

Pearson's correlations between the parameters of the lactation curves, persistency measures and each of its components were calculated using the CORR procedure of SAS version 9.4 (SAS Institute Inc.).

Results

The least-squares means and standard error of the means for the total yield, peak yield and day at peak for MY, FY and PY modelled using RRM with the Wood function for the different breed groups and lactation numbers are presented in Table 1. Lactation curves fitted to the different breed groups by lactation number for milk, fat and protein

Table 1 Least-squares means and standard error of the means of total yield (kg/cow), peak yield (kg/cow) and day at peak for milk, fat and protein yield modelled using the random regression model with the Wood function fitted to Holstein-Friesian (F), Jersey (J) and crossbred F×J cows of different lactation number milked once a day at Massey University Dairy 1 farm in 2018.

		Milk yield			Fat yield			Protein yield		
Breed	Lactation	Total yield	Peak yield	Day of peak	Total yield	Peak yield	Day of peak	Total yield	Peak yield	Day of peak
F	1	$3,273^{fg}\pm281$	$14.8^{fghi}\pm1.6$	$51^{ab}\pm4$	$158^{gh}\pm13$	$0.73^{fgh}\pm0.07$	$43^{a}\pm4$	$122^{efgh}\pm10$	$0.51^{fghi}\pm0.06$	$53^{ab}\pm5$
	2	$4,213^{cd}\pm162$	$21.0^{cd}\pm0.9$	$36^{cdef}\pm2$	$205^{c}\pm8$	$1.00^{c}\pm0.04$	$29^{cde}\pm2$	$163^{c}\pm6$	$0.77^{d}\pm0.04$	$28^{cde}\pm3$
	3	$5,279^{a}\pm106$	$26.9^{a}\pm0.6$	$32^{f}\pm1$	$241^{ab}\pm5$	$1.20^{a}\pm0.03$	$24^{e}\pm2$	$203^{a}\pm4$	$1.01^{a}\pm0.02$	$20^{f}\pm2$
F×J	1	$3,060^{gh}\pm180$	$13.9^{ghi}\pm1.0$	$49^{ab}\pm2$	$167^{efgh}\pm8$	$0.77^{efgh}\pm0.05$	$40^{a}\pm3$	$121^{fgh}\pm7$	$0.51^{ghi}\pm0.04$	$50^{ab}\pm3$
	2	$3,510^{ef}\pm140$	$16.4^{efg}\pm0.8$	$45^{b}\pm2$	$182^{def}\pm7$	$0.84^{def}\pm0.04$	$40^{a}\pm2$	$141^{de}\pm5$	$0.62^{ef}\pm0.03$	$42^{b}\pm3$
	3	$4,831^{b}\pm66$	$24.3^{b}\pm0.4$	$33^{ef}\pm1$	$251^{a}\pm3$	$1.23^{a}\pm0.02$	$26^{de}\pm1$	$195^{a}\pm2$	$0.92^{b}\pm0.01$	$23^{ef}\pm1$
J	1	$2,442^{i}\pm258$	$10.9^{i}\pm1.5$	$53^{a}\pm3$	$142^{h}\pm12$	$0.65^{h}\pm0.07$	$48^{a}\pm4$	$102^{h}\pm9$	$0.42^{i}\pm0.06$	$58^{a}\pm5$
	2	$2,593^{hi}\pm156.86$	$11.7^{hi}\pm0.91$	$50^{a}\pm2$	$152^{gh}\pm7$	$0.69^{gh}\pm0.04$	$47^{a}\pm2$	$112^{gh}\pm6$	$0.46^{hi}\pm0.04$	$54^{a}\pm3$
	3	$3,985^{d}\pm97.16$	$19.6^{d}\pm0.56$	$35^{def}\pm1$	$234^{b}\pm5$	$1.12^{b}\pm0.03$	$31^{de}\pm1$	$170^{bc}\pm4$	$0.79^{cd}\pm0.02$	$26^{def}\pm2$

[a,b,c,d,e,f,g,h,i]Least-squares means with different superscripts in each column are significantly different among combination of breeds and lactation number (P<0.05).

Table 2 Least-squares means and standard error of the means of persistency[1] for milk, fat and protein yield modelled using the random regression model with the Wood function fitted to Holstein-Friesian (F), Jersey (J) and crossbred F×J cows of different lactation number milked once a day in Massey University Dairy 1 farm in 2018.

		Milk yield				Fat yield				Protein yield			
Breed	Lactation	P1 (%)	P2 (%)	P3 (%)	P_W	P1 (%)	P2 (%)	P3 (%)	P_W	P1 (%)	P2 (%)	P3 (%)	P_W
F	1	$70^{a}\pm3$	$89^{a}\pm3$	$82^{a}\pm2$	$6.63^{a}\pm0.10$	$68^{a}\pm2$	$85^{a}\pm2$	$81^{a}\pm2$	$6.48^{a}\pm0.09$	$83^{ab}\pm3$	$95^{ab}3\pm$	$89^{a}\pm2$	$6.81^{ab}\pm0.12$
	2	$59^{bcd}\pm2$	$77^{bcde}\pm2$	$76^{cd}\pm1$	$6.25^{bcde}\pm0.06$	$61^{cd}\pm1$	$77^{cd}\pm1$	$76^{cde}\pm1$	$6.16^{cde}\pm0.05$	$69^{cd}\pm2$	$82^{cde}\pm2$	$81^{cd}1\pm$	$6.30^{cde}\pm0.07$
	3	$54^{e}\pm1$	$73^{e}\pm1$	$73^{e}\pm1$	$6.12^{e}\pm0.04$	$58^{e}\pm1$	$74^{e}\pm1$	$75^{e}\pm1$	$6.04^{e}\pm0.03$	$62^{f}\pm1$	$76^{f}\pm1$	$75^{e}\pm1$	$6.06^{f}\pm0.04$
F×J	1	$70^{a}\pm2$	$88^{a}\pm2$	$82^{a}\pm1$	$6.59^{a}\pm0.06$	$66^{a}\pm1$	$84^{a}\pm1$	$80^{a}\pm1$	$6.41^{a}\pm0.06$	$82^{a}\pm2$	$94^{ab}\pm2$	$89^{a}\pm2$	$6.77^{ab}\pm0.08$
	2	$66^{a}\pm1$	$85^{a}\pm2$	$80^{a}\pm1$	$6.48^{a}\pm0.05$	$66^{a}\pm1$	$84^{a}\pm1$	$80^{a}\pm1$	$6.42^{a}\pm0.05$	$77^{b}\pm2$	$89^{b}\pm2$	$86^{a}\pm1$	$6.60^{b}\pm0.06$
	3	$55^{de}\pm1$	$74^{de}\pm1$	$74^{de}\pm0$	$6.17^{de}\pm0.02$	$59^{de}\pm0$	$75^{de}\pm1$	$76^{de}\pm0$	$6.09^{de}\pm0.02$	$65^{e}\pm1$	$78^{ef}\pm1$	$79^{d}\pm1$	$6.16^{e}\pm0.03$
J	1	$72^{a}\pm3$	$91^{a}\pm3$	$83^{a}\pm2$	$6.67^{a}\pm0.09$	$70^{a}\pm2$	$88^{a}\pm2$	$82^{a}\pm1$	$6.57^{a}\pm0.08$	$85^{a}\pm3$	$97^{a}\pm3$	$91^{a}\pm2$	$6.90^{a}\pm0.11$
	2	$71^{a}\pm2$	$89^{a}\pm2$	$83^{a}\pm1$	$6.62^{a}\pm0.06$	$69^{a}\pm1$	$88^{a}\pm1$	$82^{a}\pm1$	$6.56^{a}\pm0.05$	$83^{a}\pm2$	$95^{a}\pm2$	$89^{a}\pm1$	$6.81^{a}\pm0.07$
	3	$59^{c}\pm1$	$77^{c}\pm1$	$76^{bc}\pm1$	$6.23^{cd}\pm0.03$	$62^{bc}\pm1$	$78^{bc}\pm1$	$78^{bc}\pm1$	$6.21^{bc}\pm0.03$	$68^{d}\pm1$	$81^{d}\pm1$	$81^{bc}\pm1$	$6.27^{d}\pm0.04$

[1]Measures of lactation persistency were P1= persistency calculated as lactation yield from day 181 to 270 divided by the lactation yield from day 1 to 90, expressed as a percentage; P2= persistency calculated as lactation yield from day 121 to 180 divided by the lactation yield from day 1 to 60, expressed as a percentage; P3= persistency calculated as the total 270-day lactation yield divided by the production of the peak lactation yield multiplied by 270, expressed as a percentage; $P_W = -(b+1)\ln(-c)$, calculated based on the parameters of the Wood function.

[a,b,c,d,e,f]Least-squares means with different superscripts in each column are significantly different among combinations of breeds and lactation number (P<0.05).

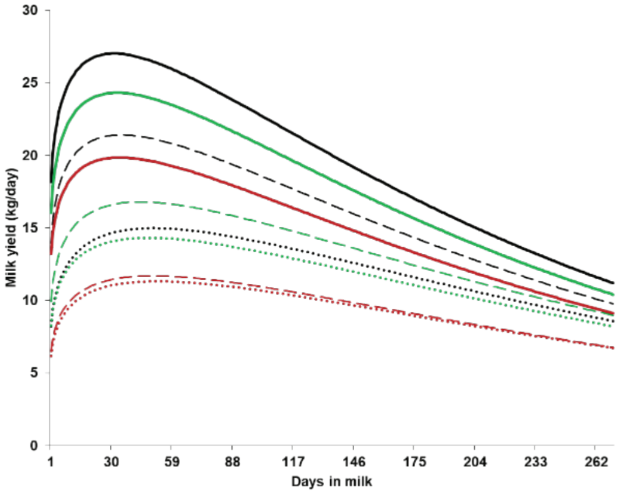
yield are presented in Figure 1. For F and F×J cows, total yields and peak yields for all milk traits significantly increased as the lactation number increased, while day of peak decreased as the lactation number increased. The same trends were also observed in J cows, however, there were no significant differences for these traits between first- and second-lactation cows. In second- and third-lactation cows, F cows produced the highest (P<0.05) total milk yield with the highest peak yield, followed (P<0.05) by F×J and then by J cows (P<0.05). In first-lactation cows, F and F×J had similar total milk yield, but higher (P<0.05) than J cows.

The differences among breeds and lactation numbers for the lactation curve of milk yield were also observed for the lactation curves for fat and protein yields, with some exceptions. In second-lactation cows, no significant differences were detected for day of peak fat yield between J and F×J. In third-lactation cows, no significant differences were detected for total fat yield, peak fat yield and total protein yield between F cows and F×J cows. No significant differences for day of peak for all milk traits were found among three breeds in third-lactation cows.

Least-squares means and standard error of the means for different measures of persistency for MY, FY and PY for different breed groups by lactation number are presented in Table 2. Persistency decreased as the lactation number increased in all three breeds. In first-lactation cows, there were no significant breed differences for persistency. In second-lactation cows, J cows had the highest protein persistency and had no significant difference to F×J cows in the persistency for milk and fat yield. In the third lactation, J cows had the highest persistency while F cows had the lowest persistency for all milk traits. Pearson correlations among the four persistency measures were strongly correlated with each other for all milk traits (r≥0.97, P<0.001).

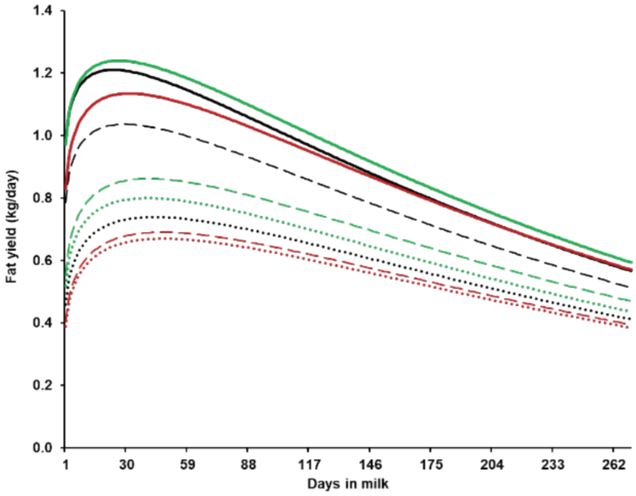
Figure 1 Lactation curves for (a) milk, (b) fat and (c) protein yields modelled using the random regression model with the Wood function fitted to Holstein-Friesian (F), Jersey (J) and crossbred F×J cows of different lactation number milked once a day at Massey University Dairy 1 farm in 2018. The panels at the right are estimates of parameters of the Wood function (a, b and c).

a)



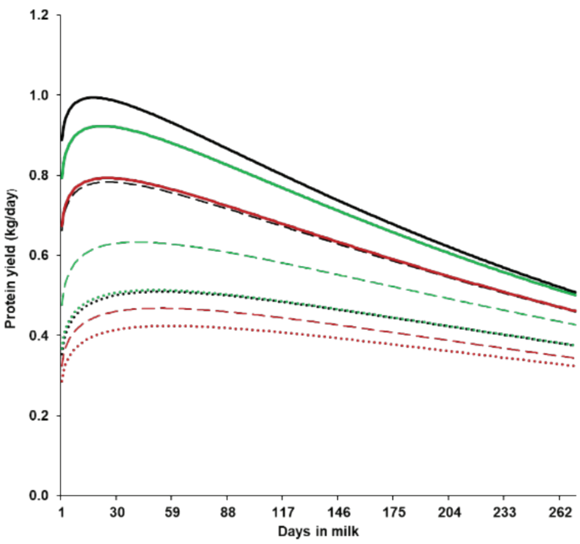
	a	b	c
F3	18.26	0.161	-0.0051
F2	14.03	0.166	-0.0048
F1	8.27	0.205	-0.0041
F×J3	16.15	0.165	-0.0050
F×J2	10.00	0.187	-0.0043
F×J1	8.29	0.190	-0.0040
J3	13.27	0.159	-0.0047
J2	6.53	0.201	-0.0040
J1	6.23	0.203	-0.0039

b)



	a	b	c
F3	0.985	0.0951	-0.00402
F2	0.789	0.1152	-0.00398
F1	0.461	0.1709	-0.00396
F×J3	0.976	0.1055	-0.00403
F×J2	0.557	0.1614	-0.00398
F×J1	0.521	0.1590	-0.00396
J3	0.833	0.1263	-0.00402
J2	0.406	0.1862	-0.00397
J1	0.390	0.1885	-0.00397

c)



	a	b	c
F3	0.891	0.0582	-0.00329
F2	0.665	0.0732	-0.00289
F1	0.354	0.1227	-0.00233
F×J1	0.796	0.0705	-0.00318
F×J2	0.477	0.1046	-0.00258
F×J3	0.369	0.1138	-0.00229
J3	0.675	0.0727	-0.00292
J2	0.324	0.1240	-0.00236
J1	0.287	0.1277	-0.00220

Table 3 Estimates of variance (on the diagonal), covariance (below diagonal) and correlation (above diagonal) matrix of the parameters (a, b and c) for daily milk, fat and protein yields modelled using the random regression model with the Wood function in cows milked once a day at Massey University Dairy 1 farm in 2018.

	a	b	c
Milk yield			
a	2.38E+01	–0.70	–0.88
b	–1.10E-01	1.03E–03	0.57
c	–2.70E-03	1.14E–05	3.90E–07
Fat yield			
a	8.22E-02	–0.90	–0.58
b	–1.26E-02	2.40E–03	0.16
c	–7.60E-06	3.68E–07	2.10E–09
Protein yield			
a	6.10E-02	–0.85	–0.92
b	–7.71E-03	1.35E–03	0.69
c	–1.10E-04	1.23E–05	2.34E–07

Estimates of (co)variance matrix **W** and correlation among of the parameters (a, b, and c) for MY, FY and PY modelled using RRM with the Wood function are presented in Table 3. The variance for parameter a was larger than the variance for the parameters b and c for all milk traits. The estimates of the correlations among the parameters of the Wood function for milk yield were negative and moderate. For protein yield, the correlation between parameter a and b and between a and c were moderate and negative, but the correlation between b and c was low and negative. For fat yield the correlation between a and b was moderate and negative, but the other correlations were close to zero.

Discussion

Significant differences were observed in the shape of the lactation curves for the different breed groups and lactation numbers (Figure 1). Within first-lactation cows, the F×J cows had the greatest initial production of milk, fat and protein. In the other lactation numbers, however, the initial production of F×J cows was intermediate between F cows and J cows. The individual variations in the slope of the increasing and the decreasing phases for lactation curves of daily PY were smaller than that of daily MY or FY, which is consistent with previous research in OAD milking systems (Hickson et al. 2006), as well as in a system with higher milking frequency (Schutz et al. 1990).

Many studies showed that total yield and peak yield increased as the lactation number increased, while day at peak decreased as the lactation number increased (Wood 1969; Stanton et al. 1992; Tekerli et al. 2000; Horan et al. 2005); these trends were also found in the current study. Previous studies showed that F cows had the highest total MY (Hickson et al. 2006) while F×J cows had the highest total FY and PY, compared to J cows (Lembeye et al. 2016). In the current study, however, F cows of all lactation numbers had the highest total yields and peak yields for all milk traits and no significant differences were found between F and F×J cows for FY and PY in the first and third lactation. Hickson et al. (2006) reported no significant differences between the day of peak for Jersey and Holstein-Friesian in a OAD milking system. In the current study, breed effects were only found in the second lactation cows for all milk traits.

It has been reported that first-lactation cows have higher persistency for MY than do multiparous cows (Wood 1980; Stanton et al. 1992; Gengler 1996; Tekerli et al. 2000), a result also found in the present study. Miller et al. (2006) reported that primiparous cows were more persistent than multiparous cows because they were able to maintain the population of secretory cells at a higher level.

Lembeye et al. (2016) reported that J cows had the highest persistency for FY and that F×J cows had the highest persistency for MY and PY, while F cows had the lowest persistency in an OAD milking system. In the current study, no breed differences for persistency in any milk traits were found in the first-lactation cows. In third-lactation cows, J cows had the highest persistency compared to other breeds for all milk traits. Results of the current study suggested that J cows were more suitable for an OAD milking system than F cows. Jersey cows are reported to be able to accumulate milk in the udder for longer periods than F cows (Davis et al. 1999).

Although the persistency estimates varied using different measures, correlations among four persistency measures in the current study were all strongly and positively correlated ($r \geq 0.97$) and were significantly different from zero ($P<0.001$) for each of the milk traits, indicating that these measures express the lactation curve in the same way. However, correlations between different persistency measures have been reported to vary from 0.24 to 0.91 (Madsen 1975; Tekerli et al. 2000; Lopez-Villalobos 2005) depending on the definition. Few studies have investigated the correlations among persistency measures based on the parameters of the Wood function and other measures. Madsen (1975) reported significant correlations among five measures of persistency ranging from 0.42 to 0.91. Those differences in results may not only be due to different persistency measures used, but also to the inaccurate prediction of the lactation yield.

Estimates of (co)variances provided in Table 3 can be used for estimation of parameters of the Wood function and predicted yields on new cows or cows with few herd-test records using the properties of RRM as illustrated by Schaeffer and Dekkers (1994). Parameter a of the Wood function is associated with the level of milk production at the start of the lactation; the higher the a value, the higher the level of production at the start of the lactation. The parameter b is associated with the peak yield; the higher the b value, the higher the peak yield. The parameter c is associated with the level of production at the end of the lactation; the lower the estimate (more negative), the lower the yield after the peak yield. The strong negative correlations between parameters a and b and between a and c, with a medium positive correlation between b and c, indicated that cows with a higher initial yield would have slower increasing rate before the peak, and a low level of production after the peak yield. The trend of these correlations was similar for the MY, FY and PY, but the correlation between a and b was more negative for FY than for MY and PY, and the correlation between b and c was weaker for FY than MY and PY. The strong positive correlations between parameters b and c for daily MY and PY, indicated that cows with a greater increasing rate before the peak had a greater decreasing rate after the peak, leading to a lower persistency. Similar results were obtained in previous studies (Tekerli et al. 2000; Macciotta et al. 2011). For daily FY, greater rate of increase before the peak may not result in lower persistency due to the lower correlation between parameters b and c (r=0.16).

Conclusions

Holstein-Friesian cows in their third lactation had the greatest total yield, peak yield and earliest day at peak for all milk traits, but they had the lowest persistency compared with all other lactations and breeds. Jersey cows of third lactation had the greatest persistency for all persistency measures. In first-lactation cows, there were no significant breed differences for persistency. Persistency measures were strongly correlated with each other. The conclusion from this study is that the parameters of the lactation curve (peak yield, day of peak and persistency) can be precisely estimated using RRM with the Wood function.

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