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Prediction of 305-day lactation milk, fat and protein yields using Legendre polynomials and test-day yields from different parts of lactation

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Applicability was evaluated of second-, third- and fourth-order Legendre polynomials (LPs) as lactation curve models for prediction the 305-day lactation yields. First lactation milk, fat and protein yields were calculated using the standard lactation curve method (LCM) and data collected during lactations truncated at 60, 100, 200 and 305 days-in-milk. All results were compared with the official lactation yields of cows. Data consisted of 5,289,576 test-day yields from 668,964 lactations of Black-and-White heifers. Standard lactation curves were modelled by LPs of the second (L2), third (L3) and fourth (L4) orders within 64 classes of genetic group by age at calving by season of calving. LPs of the highest order (L4) were the best-fitted lactation curve models, followed by L2 and L3 polynomials, showing that LPs of even orders are more suitable for fitting lactation curves. It is concluded that 305-day yields of heifers can be predicted with sufficient accuracy when the lactation curve parametres are derived using tests from the first 200 days-in-milk.

KEY WORDS: cow / lactation / Legendre polynomial / test-day

Over many years in Poland, as in other countries, the 305-day lactation yields of dairy cows have been calculated based on monthly test-day yields of milk-recorded cows. The method is to interpolate the mean yield over the interval between monthly tests and to accumulate the resulting value after each test. Intervals between two tests should be close to 30 days and erroneous predictions of lactation yields may appear if this condition is not fulfilled [Schaeffer and Burnside 1976].

During the past few decades lactation curves have been modelled by many authors [Schaeffer *et al.* 1977, Batra and Lee 1985, Keown *et al.* 1986, Wilmink 1987, Schaeffer and Jamrozik 1996, Olori and Galesloot 1999, Vargas *et al.* 2000,] intending to improve methods of predicting 305-day lactation yields. Methods developed during the last two decades have used information about standard lactation curves and covariances between test-day yields [Wilmink 1987, Schaeffer and Jamrozik 1996]. Standard lactation curves describe the average lactation patterns observed within subclasses of effects directly affecting the curves (e.g., lactation number, breed, age and season of calving). The lactation curve parametres for an individual cow are estimated using the standard lactation curve for the subclass to which the cow belongs. The estimated parametres are then used to calculate the 305-day lactation yield. More accurate predictions of lactation yields are obtained if covariances among test-day yields are accounted for [VanRaden 1997].

Lactation curves can be described using different mathematical functions [Ali and Schaeffer 1987, Wilmink 1987, Guo and Swalve 1995]. Legendre polynomials (LPs) have recently became very popular [Kirkpatrick *et al.* 1994] as having many advantages over other models. LPs are orthogonal, easy to fit, and linear as functions of parametres [Pool *et al.* 2000]. The main disadvantage is that their parametres have no biological meaning. This, however, does not matter when Legendre polynomials are used.

The objective of this study was to compare the LPs of second-, third- and fourth-order as lactation curve models applied for calculation of 305-day lactation yields of Polish Black-and-White cows when data accumulate during the lactation.

Material and methods

The first data file (DF1) consisted of 5,289,576 test-day yields (TDYs) of milk, fat and protein recorded for 668,964 first lactations of Black-and-White cows (upgraded with Holstein Friesians – HF) that from 1995 through 2003 calved at the age of 18-48 months. Each cow was required to have at least four test-day yields per lactation. Days in milk (DIM) were restricted to those between 5 and 305, daily yields of milk between 1.5 and 85 kg, and fat and protein content between 1.5 and 8.5%. The parametres of standard lactation curves were estimated within subclasses of genetic group by age at calving by season of calving. There were eight genetic groups (every 12.5% of HF genes), four groups of age at calving (18-24, 25-30, 31-36, 37-48 months) and two seasons of calving (April-September and October-March), making 64 different standard lactation curves fitted to data from DF1.

The second data file (DF2) was created from DF1 and contained 3,736,695 TDYs of 446,147 first lactations of heifers that had the last TDY after day 200 of lactation and were present in the official milk recording database (Tab. 1). This file was used to estimate the parametres of individual lactation curves of cows and to predict 305-day lactation yields by the standard lactation curve method (LCM). The linear equations for the LCM procedure used in this study were those given by Schaeffer and Jamrozik

Table 1. Number of lactations and test-day (TD) records by genetic group, calving age and season of calving

Item	Number of lactations	Number of TD records
Genetic group (% of HF genes)		
1 (<0-12.5)	11,788	99,821
2 (12.5-25.0)	11,656	99,742
3 (25.0-37.5)	26,725	224,967
4 (37.5-50.0)	66,446	537,161
5 (50.0-62.5)	82,264	676,379
6 (62.5-75.0)	83,755	700,328
7 (75.0-87.5)	92,557	785,904
8 (87.5-100.0)	70,956	612,393
total	446,147	3,736,695
Calving age (months)		
1 (18-24)	91,178	740,042
2 (25-30)	265,648	2,233,836
3 (31-36)	75,616	646,152
4 (37-48)	13,705	116,665
total	446,147	3,736,695
Season of calving		
1 (October-March)	247,737	2,077,301
2 (April-September)	198,410	1,659,394
total	446,147	3,736,695

[1996] as follows:

$$(\mathbf{X'R^{-1}X} + \mathbf{G^{-1}})\ \mathbf{c} = \mathbf{X'R^{-1}y} + \mathbf{G^{-1}c_0}$$

where:

c is the vector of parametres of cow's lactation curves for each trait (milk, fat and protein yield);

$\mathbf{X'R^{-1}X} = \sum_{k=1}^{n} \mathbf{X'_k R_k^{-1} X_k}$, $\mathbf{X'R^{-1}y} = \sum_{k=1}^{n} \mathbf{X'_k R_k^{-1} y_k}$, $\mathbf{y_k}$ is the vector of milk, fat and protein daily yield of a given cow on the *k*-th test;

$\mathbf{X_k}$ is the 3×9 incidence matrix;

$\mathbf{R_k}$ is the 3×3 matrix containing (co)variances among yields on the *k*-th test at day t of lactation;

n is the number of tests;

G is the 9×9 matrix of variances and covariances among the parametres in **c**;

$\mathbf{c_0}$ is the vector of standard lactation curve parametres.

The vector $\mathbf{c_0}$ represents the parametres of standard lactation curves estimated across all cows within the given cow's subclass of genetic group by age at calving and by season of calving. Both matrices (**G** and $\mathbf{R_k}$), were derived for each genetic group.

Only cows with more than eight TDYs and the first TDY before 50 DIM were used to estimate the **G**.

Below are given LPs of the second (L2), third (L3) and fourth (L4) orders used to model standard ($\mathbf{c_0}$) and individual ($\mathbf{c}$) lactation curves [Kirkpatrick *et al.* 1994]:

t is

L2: $\mathbf{y(t) = c_0 + c_1\sqrt{3}x + c_2\sqrt{\tfrac{5}{4}}(3x^2 - 1)}$;

L3: $\mathbf{y(t) = L2 + c_3\sqrt{\tfrac{7}{4}}(5x^3 - 3x)}$;

L4: $\mathbf{y(t) = L3 + c_4\tfrac{3}{8}(35x^4 - 30x^2 + 3)}$,

where:

$$\mathbf{x = -1 + 2\frac{t - t_{min}}{t_{max} - t_{min}}}$$

$\mathbf{t_{min}}$, $\mathbf{t_{max}}$ are the minimum and maximum DIM (5 and 305, respectively).

All three LPs (L2, L3 or L4) were applied in the LCM method giving predicted 305-day lactation yields of milk, fat and protein. Because the true lactation yields of the cows were not available, all lactation yields predicted by LCM were compared with yields estimated with the routine method (RM). Additionally, to check whether the parameters estimated for different lactation curve models are sensitive to the length of records in progress, daily yields of heifers up to 60 DIM (file DF60), 100 DIM (file DF100) and 200 DIM (file DF200) were extracted from data file DF2. The LCM procedure was applied using also data from DF60, DF100 or DF200. Different lactation curve models fitted to the data from lactations truncated to different lengths were compared based on 305-day lactation yields predicted by LCM. All comparisons were related to the official lactation yields of the cows studied.

Results and discussion

Numbers of lactations and tests per lactation by genetic group, by age at calving and by season of calving are presented in Table 1. The average number of TDYs per lactation was 8.4. Only 26 % of cows had less than 50% HF genes. Most cows (21%) belonged to the 7th genetic group (75-87.5% HF genes). Cows calved mainly at the age of 25-30 months (60%) and only 3% of them were older than three years when calving. The numbers of lactations starting in both defined seasons of calving were comparable (45% and 55%). Means for daily yields of milk, fat and protein are shown in Figure 1. The mean daily milk yield amounted to 17.1 kg (SD=5.15), with the peak of 21.5 kg at day 34 of lactation. Mean daily yield of fat was 0.71 (SD=0.24) and that of protein 0.55 (SD=0.18) kg with maximum of 0.95 kg on day 9 and 0.70 kg on day 6, respectively. The peak protein yield appeared very early, *i.e.* about 4 weeks before the maximum milk yield was achieved. The lowest variation within test-day yields of milk and protein occurred during the first month of lactation, whereas variation in daily

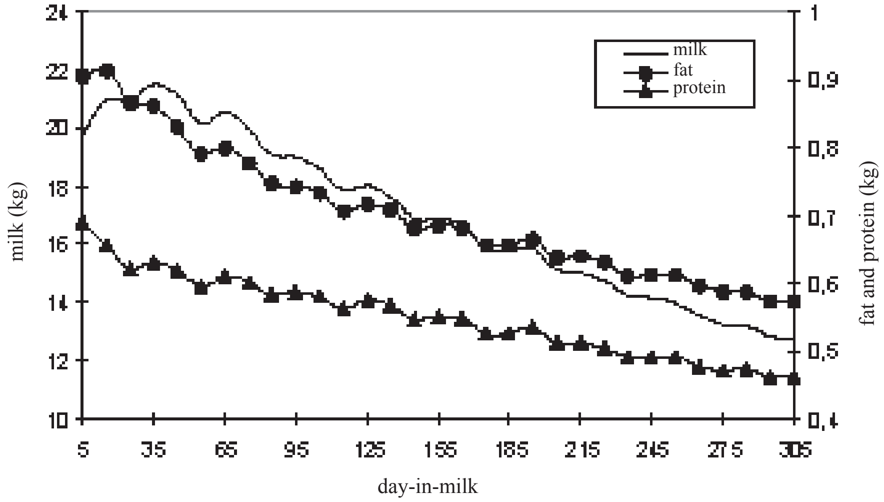

Fig. 1. Observed mean daily yield of milk, fat and protein in first lactation.

fat yield at that time was the greatest.

Mean 305-day yield of milk, fat and protein predicted by LCM using LPs of different orders (L2, L3 or L4) and files with increasing number of information (DF60, DF100, DF200, DF2) are presented in Table 2, while mean lactation yields predicted with RM in Table 3; the comparisons among models were related to RM results as they constituted the only available source of information on the lactation yields of the cows considered.

Generally, means and ranges (min., max.) of 305-day yields given in Table 2 appeared higher than those in Table 3. The exception was the mean protein yield obtained using the L3 and data from the first two months (DF60), which was by far less than all other predictions of mean protein yield, including that by RM. Careful analysis of the DF60 data file showed that in this case about 15% cows had very low protein yield predictions, and for more than 29,000 cows (6.5% of a total) the difference between yields predicted with L3 and RM was wider than three standard deviations. Moreover, because in our data the peak yield of protein was achieved, in fact, at the very beginning of lactation, the mean lactation curve for daily protein yield of those cows was shaped differently from lactation curves for milk and fat yield (Fig. 1). It is possible that LPs of odd order (e.g. L3) are inappropriate for modelling lactation curves when they vary much from the standard what may lead to very low predictions of protein yield.

The 305-day yields of all analysed traits were more variable when predicted by LCM, although in few cases (for L4 and DF60, or L4 and DF2) their standard deviations were smaller than those resulting from RM. The smallest differences between lactation yields when predicted with LCM and RM were found using the L4 as the lactation

Table 2. Means for 305-day lactation yield, their standard deviations (SD) and ranges (min., max.) predicted using second-order (L2), third-order (L3) and fourth-order (L4) Legendre polynomials and TDY's from different data files (DP60, DP100, DP200, DP1)

File	Trait (yield)	L2 mean	L2 SD	L2 min	L2 max	L3 mean	L3 SD	L3 min	L3 max	L4 mean	L4 SD	L4 min	L4 max
DP60	milk	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	fat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	protein	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DP100	milk	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	fat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	protein	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DP200	milk	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	fat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	protein	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DP1	milk	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	fat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	protein	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 3. Means for 305-day lactation yield, their standard deviations (SD) and ranges (min., max.) predicted with the routine method (RM)

Trait	Mean	SD	Min.	Max.
Milk	5,098	1,347	2,000	16,050
Fat	209.6	59.3	60.3	730.3
Protein	163.8	45.6	54.8	326.4

curve model, followed by L2 and L3 polynomials. LPs of even orders produced more accurate predictions of 305-day yields for all traits.

As expected, the best fit and the most similar predictions of lactation yields for all traits were obtained using all available TDY data (DF2). The differences between predicted yields were highest for DF60 and decreased when data accumulated, although they were still large for protein yields when L3 and L4 or L3 and L2 were compared. This means that among the models applied, L3 polynomials gave the poorest fit, especially for protein yield.

In an earlier study by Ptak and Frącz [2002] when the Wilmink function was used as a lactation curve model, mean 305-day yields of milk, fat and protein as well as their ranges were also greater than those calculated with RM. The results were similar when the Ali and Shaeffer model was applied for modelling individual and standard lactation curves of Polish Black-and-White cows [Frącz and Ptak 2003]. Both the Wilmink and Ali and Schaeffer functions gave lactation yield estimates much more different from the official lactation yields than did the estimates from Legendre polynomials. However, they were much more applicable for fitting protein lactation curves.

Linear correlations between 305-day yields of milk, fat and protein predicted with LCM using different lactation curve models and data files are given in Table 4, while Table 5 presents the correlations between lactation yields of all three traits as predicted by both LCM and RM. The more TDY data used in the calculations, the higher the correlation values regardless of the lactation curve model chosen for LCM. The highest similarity between 305-day yields of all traits was observed for L4 predictions. There was no practical difference between the 305-day yields calculated using data from the first 200 DIM (DF200) *vs* those calculated from whole lactation (DF2) data. The difference between yields was significant when DF60 was replaced by DF100. When DF100 was replaced by DF200 this difference was much smaller. It seems that collecting TDYs until 200 DIM is satisfactory for accurate prediction of cows' lactation yields.

All correlations between yields obtained with the use of L4 or L2 polynomials and TDYs from DF2 were found equal or greater than 0.90, whereas with the L3 model, only that between milk and fat yield amounted to 0.90, the remaining being smaller than 0.70 (Tab. 4). The rather low values of the correlations between milk and protein as well as between fat and protein yields could partly be explained by the fact that the

Table 4. Coefficients of linear correlation between 305-day yields of milk (M), fat (F) and protein (P) predicted by the standard lactation curve method (LCM) with different lactation curve models and TD data files

Model	File	Correlation coefficient		
		M × F	M × P	F × P
L2	DF60	0.73	0.89	0.74
	DF100	0.81	0.93	0.81
	DF200	0.88	0.96	0.89
	DF2	0.90	0.98	0.91
L3	DF60	0.81	0.35	0.48
	DF100	0.82	0.32	0.63
	DF200	0.87	0.61	0.64
	DF2	0.90	0.68	0.67
L4	DF60	0.88	0.96	0.88
	DF100	0.89	0.96	0.89
	DF200	0.85	0.95	0.86
	DF2	0.90	0.97	0.91

Table 5. Coefficients of linear correlation between 305-day yields of milk (M), fat (F) and protein (P) predicted by routine (RM) and standard lactation curve (LCM) methods with different lactation curve models and data files chosen for LCM

Model	File	Correlation coefficient		
		M	F	P
L2	DF60	0.77	0.68	0.72
	DF100	0.86	0.80	0.84
	DF200	0.97	0.96	0.96
	DF2	0.99	0.99	0.99
L3	DF60	0.82	0.72	0.28
	DF100	0.84	0.77	0.38
	DF200	0.96	0.92	0.54
	DF2	0.99	0.98	0.68
L4	DF60	0.83	0.81	0.81
	DF100	0.88	0.86	0.87
	DF200	0.94	0.90	0.93
	DF2	0.99	0.99	0.99

lactation curves for protein yield differed significantly from typical lactation curves (Fig. 1). Fourth-order LPs seem to be the best model for fitting lactation curves of Polish Black-and-White cows.

These conclusions were confirmed by the relatively high correlation coefficients between 305-day yields of all milk traits predicted by two methods: LCM with L4 polynomials and RM (Tab. 5). When lactation yields were predicted on the basis of TDY from DF60, the correlations for all models were the lowest, although higher than 0.80 in the case of L4. Third-order polynomials (L3) gave a very low correlation for protein yield (less than 0.70) even when all available TDYs were used (DF2) – Table 5.

Schaeffer and Jamrozik [1996] compared two methods of 305-day lactation yield prediction (with the use of standard lactation curves *vs* the test interval method) and concluded that they did not differ significantly when the tests were regularly spaced. Correlation between predicted and true 305-day yield increased with increasing number of tests (from 0.62-0.65 for one test to 0.99-1.00 for nine tests). In almost all cases the correlation coefficients exceeded 0.90 when the prediction was based on at least four tests. Olori and Galesloot [1999] confirmed that the correlations between projected and official 305-day lactation yields increased with progressing length of the records. The projected yields were calculated using projection factors derived on the basis of standard lactation curves. The correlation coefficients between official and predicted first lactation protein yields were 0.84, 0.89, 0.96 and 0.99 for lactations truncated at 50, 100, 200 and 300 DIM, respectively. Similar relations were found by Wilmink [1987] who claimed the correlations between predicted and realized 305-day milk yields to increase from about 0.86 to 0.99 as the day of the last test progressed from 50th to 210th.

Many comparisons of various methods of predicting 305-day lactation yield lead to the conclusion that the routine method (RM) is satisfactory as long as its assumptions are fulfilled [Schaeffer and Burnside 1976, Schaeffer and Jamrozik 1996, Ptak and Frącz 2002]. On the other hand, methods based on lactation curve models (e.g. LCM) have some advantages over those used routinely, as they deliver statistics useful in management, such as persistency of lactation, day of peak milk yield, as well as peak milk yield, and average curves for herds' production. The latter could be used to make within-herd comparisons. From an economic point of view, all those statistics could be valuable sources of information. Moreover, knowledge of cows' lactation curves may help detecting test-day yields that are too high or too low compared with previous tests, as well as correcting yields relatively easily.

The results presented here show that Legendre polynomials of even order (L2 and L4) were more useful than odd order (L3) polynomials when used as lactation curve models in LCM. The L4 were the best, followed by L2 and L3 polynomials. The 305-day yields were predicted with satisfactory accuracy when the test-day records from the first 200 days-in-milk were used. Accuracy was poorer when tests were made during the first 60 or 100 days of lactation. More detailed research should be undertaken when data on the true lactation yields of Polish Black-and-White cows are available.

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Przewidywanie 305-dniowych wydajności mleka, tłuszczu i białka za pomocą wielomianów Legendre'a i próbnych udojów z różnych części laktacji

S t r e s z c z e n i e

Badano przydatność wielomianów Legendre'a (LPs) drugiego, trzeciego i czwartego stopnia (odpowiednio L2, L3 i L4) do obliczania 305-dniowych wydajności mleka, tłuszczu i białka w laktacjach pierwiastek Wykorzystano 5 289 576 próbnych udojów z 668 964 laktacji krów cb z różnym udziałem krwi hf, cielących się w latach 1995-2003. Zastosowano metodę wykorzystującą tzw. standardowe krzywe laktacji *(lactation curve method* – LCM*)* oraz (ko)wariancje między dziennymi wydajnościami krów. Standardowe krzywe laktacji, które opisują przebieg laktacji dla grup krów, obliczono w obrębie 64 podklas: grupa genetyczna (% krwi hf) × klasa wieku ocielenia × sezon ocielenia, za pomocą wielomianów L2, L3 lub L4, a następnie wykorzystano je do dopasowania indywidualnych krzywych laktacji. Indywidualne krzywe laktacji wyznaczano na podstawie próbnych udojów wykonanych w ciągu 60, 100, 200 lub 305 dni laktacji. Wydajności laktacyjne obliczono sumując dzienne wydajności, szacowane na podstawie dopasowanej krzywej laktacji. Podstawę do porównania wydajności oszacowanych za pomocą standardowych krzywych laktacji stanowiły 305-dniowe wydajności obliczone metodą rutynową *(routine method* – RM).

Najbardziej przydatny do przewidywania wydajności laktacyjnych okazał się wielomian L4, a następnie wielomiany L2 i L3. Wielomiany stopnia nieparzystego (L3) były najmniej przydatne do modelowania krzywych laktacji. Wnioskuje się, że wydajności laktacyjne można z zadowalającą dokładnością przewidywać stosując metodę LCM oraz próbne udoje z pierwszych 200 dni laktacji. Zastosowanie w praktyce wielomianów Legendre'a stopnia czwartego wymaga jeszcze dalszych badań, przy czym wskazane byłoby porównanie metody LCM z rzeczywistymi wydajnościami laktacyjnymi krów.