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Fitness of Lactation Curve Functions to Daily and Monthly Test-Day Milk Data in an Ethiopian Multi-Breed Dairy Cattle Population

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ABSTRACT

The objectives of this study were to identify the lactation curve function that had the best fit to daily and monthly test-day milk data and to evaluate the factors affecting parameters of the best fit lactation curve function for an Ethiopian dairy cattle population. An incomplete gamma (IG), a modified incomplete gamma (MIG; $b = 1$) and an inverse polynomial (IP) function were compared using 6,717 lactation milk records of 2,064 cows from the Bako, Holetta and Debre Zeit Research Centers, Ethiopia. Breed groups were Horro (H), Boran (B), B × Friesian, H × Friesian, B × Simmental, H × Simmental, B × Jersey and H × Jersey. The MIG and IG were log-transformed to linear form before fitting. The functions were compared based on the least squares means (LSM) of R^2 (LSM R^2) and adjusted R^2 values and on the accuracy of lactation milk yield prediction. The statistical model included herd-year-season of calving, parity, data type, breed group, lactation curve function, and the interactions of data type × function and breed × data type × function as fixed effects, and the residual as a random effect. The MIG, IP and IG functions ranked from the best to the worst fit based on LSM R^2 and adjusted R^2. The LSM R^2 and adjusted R^2 were significantly ($P < 0.001$) different among all classes of fixed effects considered in the model. The LSM R^2 and adjusted R^2 for the MIG function were 0.90 and 0.89, respectively. All functions fitted to monthly test-day better than to daily milk data. The MIG function had the best fit ($P < 0.001$) to daily milk data, but both the MIG and IP functions had a similar fit to monthly test-day milk data based on the LSM of adjusted R^2. The $ln(a)$ and c from the MIG function with daily and monthly test-day milk data, and the A_0, A_1 and A_2 from the IP function with monthly test-day data were different among breed groups, parities and herd-year-season classes (at least $P < 0.05$). The MIG function predicted the lactation milk yield from the monthly test-day milk with the lowest prediction error ($P < 0.001$) compared to the IP and IG functions. Thus, the MIG function could be recommended to model lactation milk data from monthly test-day milk in the studied dairy cattle population.

Keywords: cattle, lactation curve function, prediction, test-day

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INTRODUCTION

Ethiopia is endowed with a diverse range of indigenous cattle breeds (Alberro and Hailemariam, 1982). However, limited research has been done to improve the indigenous cattle breeds. Efforts made to improve the indigenous breeds through crossbreeding with exotic sire breeds are not supported by periodic genetic evaluations due to mainly the lack of a data recording system. Information available on genetic improvement (for example, Demeke *et al*., 2003) of Ethiopian cattle is limited to research center-based data. Test-day milk recording could be an option to solve the problems of daily milk recording for genetic evaluations.

Several methodologies have been proposed for the genetic evaluation of production traits for dairy cattle based on test-day records. Currently, the most commonly used test-day models are random regression models that consider a mean curve in the population and model individual deviations from this mean curve for each animal (Jaffrezic *et al*., 2002). Lactation curve functions could also be used as a tool for genetic evaluation by extending incomplete lactations, predicting test-day milk, fat and protein yield, predicting lactation milk yield and adjusting test-day milk for environmental effects occurring on the day of milk recording (Macciotta *et al*., 2002; Mayeres *et al*., 2004).

In order to use lactation curve functions in genetic evaluation, identification of the best fitting function is a prerequisite. Different functions are available to model lactation profiles and have been compared for their goodness of fit to different data types, breeds, herds and species (Papajcsik and Bodero, 1988; Sherchand *et al*., 1995). However, the results were not consistent among the various studies due to differences in the functions compared, methodology used to fit the functions, variations among herds and the type of data used to fit the functions. Despite the better fit obtained from the more complex models (Sherchand *et al*., 1995), simpler models tend to be preferred by many researchers. Wood's incomplete gamma function is the most commonly used model (Papajcsik and Bodero, 1988; Sherchand *et al*., 1995) to fit different data types, because its three parameters (a, b and c) can be related to the initial and peak milk yield, days to peak and persistency of lactation. Thus, the objectives of this study were to identify the best fit lactation curve function to daily and monthly test-day milk data, and to characterize factors that affect the parameters of the best fit lactation curve functions.

MATERIALS AND METHODS

Description of the study area and data

The study was based on data from the Bako, Debre Zeit and Holetta Research Centers, Ethiopia. The Bako Agricultural Research Center is located 250 km west of Addis Ababa at an altitude of 1,650 m above sea level. The Center receives a mean annual rainfall of 1,200 mm in a bimodal distribution, 80% of which falls from May to September and has a mean relative humidity of 59% and mean minimum and maximum temperatures of 13.5 and 27^{o}C, respectively (Gebregziabher *et al*., 2003). The International Livestock Research Institute (ILRI) Debre Zeit Research Station is located 50 km southeast of Addis Ababa at an altitude of 1,920 m above sea level. Climatic data for the Station shows: the mean annual rainfall of 850 mm has a bimodal distribution—about 84% of the rain falls during the long rainy season (June to September) and the remainder during the short rainy season (March to May); the dry season extends from October to February; The mean minimum and maximum temperatures are 15 and 28°C, respectively, and the mean relative humidity is 63% (Haile *et al*., 2011). The Holetta Research Center is located 45 km west of Addis Ababa at an altitude of 2,400 m above sea level. The mean annual rainfall is about 1,200 mm with the main rainy season occurring between June and October and the dry season from

November to February (Demeke *et al*., 2003).

Milk data from the Boran and Horro indigenous breeds (Alberro and Hailemariam, 1982) and their crosses with Friesian, Jersey and Simmental exotic sire breeds recorded at the Bako and Holetta Research Centers; and milk data from Boran and Boran × Friesian crosses at the Debre Zeit Research Station were used for this study. The data covered a period from 1977 to 2010 for the Bako and Holetta Centers and from 1989 to 2006 for the Debre Zeit Center. Data entry, sorting and preparation for the analysis were done using Microsoft® Excel® software according to Frye (2007) and the Statistical Analysis System (SAS) software (SAS, 2003). Daily milk yield recorded monthly starting from the date of calving was used as the monthly test-day milk yield. Based on the distribution of the dataset, longer lactations were truncated to 305 d and shorter lactations (less than 90 d) were excluded before fitting to the functions. Thus, the analysis was based on 6,717 milk records of 2,064 cows.

Goodness of fit of the lactation curve functions

Three lactation curve functions (the incomplete gamma (Wood, 1967), modified incomplete gamma (Papajcsik and Bodero, 1988) and inverse polynomial (Nelder, 1966) functions) were compared for their fit to the daily and monthly test-day milk data. The incomplete gamma (IG) function is represented by $y_t = at^be^{-ct}$ where t is the length of time since calving, y_t is milk yield at time t after calving and a, b and c are parameters of the functions. The parameter a is a scaling factor associated with the average yield, b is related to pre-peak curvature and c is related to post-peak curvature. The modified incomplete gamma (MIG) function is described as $y_t = ate^{-ct}$, where the parameter b of Wood's IG function is set as one. The inverse polynomial (IP) function is described as $y_t = t(A_0 + A_1t + A_2t^2)^{-1}$, where y_t is the milk yield at time t, and A_0, A_1 and A_2 are function parameters associated with the rate of increase to peak production, the average slope of the lactation curve and the rate of decline after peak, respectively (Batra, 1986). The log-transformed linear form of IG ($ln(y_t) = ln(a) + bln(t) + (-ct)$) and MIG ($(ln(y_t/t) = ln(a) + (-ct)$) were used to fit to the data. The IP function was rearranged as $t/y_t = A_0 + A_1t + A_2t^2$ to fit to the data. These functions were fitted to daily and monthly test-day milk data from each lactation of each cow using the regression procedure of SAS (SAS, 2003).

The goodness of fit of the three lactation curve functions was compared based on the analysis of variance of the R^2 and adjusted R^2 values obtained from the regression analysis of each lactation from each cow (Batra, 1986; Olori *et al*., 1999) using the general linear model of SAS (SAS, 2003). The model shown in Equation 1 was used to analyze the R^2 and adjusted R^2:

$$Y_{ijklmn} = \mu + HYS_i + P_j + G_k + F_l + D_m + (F \times D)_{lm} + (G \times F \times D)_{klm} + e_{ijklmn} \quad (1)$$

where Y_{ijklmn} is the R^2 or adjusted R^2 estimated using the l^{th} function that was fitted to the m^{th} data type of the n^{th} cow that calved in the i^{th} herd-year-season, j^{th} parity and k^{th} breed group, μ is the overall mean, HYS_i is the i^{th} calving herd-year-season subclasses (i = 1 to 325), P_j is the j^{th} parity (j = 1 to 7 with parity 7 including ≥ 7 parities), G_k is the k^{th} breed group (k = 1 to 8; Horro (H), Boran (B), B × Friesian, H × Friesian, B × Simmental, H × Simmental, B × Jersey, and H × Jersey), F_l is the l^{th} lactation curve function subclass (l = 1 to 3; IG, MIG, and IP), D_m is the m^{th} data type (m = 1 to 2; daily and monthly test-day milk data), $(F \times D)_{lm}$ is the two factor interaction of l^{th} function and m^{th} data type, $(G \times F \times D)_{klm}$ is the three factor interaction of k^{th} breed, l^{th} function and m^{th} data type, e_{ijklmn} is the residual error associated with y_{ijklmn} and it was assumed that $e \sim (0, \sigma_e^2)$.

For each considered fixed effect, the least squares means were estimated and they were compared among subclasses after applying the Bonferroni correction (SAS, 2003).

Parameters of the best fit lactation curve functions

After comparing the three lactation functions using the procedure described above, the best fit lactation curve function was selected for monthly and daily milk data based on the analysis of variance of the R^2 and adjusted R^2 values. The parameter estimates of the best fit lactation curve function from individual cows were analyzed using a statistical model that considered the effects of the herd-year-season of calving, breed group and parity of the cow.

Prediction of lactation milk yields

Comparisons were made between the actual lactation milk yield of a cow (cumulative sum of daily milk yields over a lactation of a cow), the lactation milk yield of a cow predicted using the IG, MIG and IP functions fitted to daily and monthly test-day milk data, and the lactation milk yield of a cow estimated using the test-interval method. The milk yield from the test-interval method was calculated as described by Koonawootrittriron *et al*. (2002) and is shown in Equation 2:

$$\boldsymbol{LMY} = (\boldsymbol{P}_1 \times \boldsymbol{D}_1) + \sum_{n=2}^{k}[\frac{(\boldsymbol{P}_i + \boldsymbol{P}_{i-1})}{2} \times \boldsymbol{D}_i] + (\boldsymbol{P}_{k+1} \times \boldsymbol{D}_{k+1}) \quad (2)$$

where ***LMY*** is the lactation milk yield of a cow, $\boldsymbol{P_1}$ is the test-day milk yield sampled in the first month after calving, $\boldsymbol{D_1}$ is the interval between the date milking started after calving and the date of the first test-day milk sample; $\boldsymbol{P_i}$ is the test-day milk yield sampled in month $\boldsymbol{i}$ ($\boldsymbol{i}$ = 2, … , k), $\boldsymbol{D_i}$ is the interval between test-days in months $\boldsymbol{i}$ - 1 and $\boldsymbol{i}$ ($\boldsymbol{i}$ = 2, … , k), $\boldsymbol{P_{k+1}}$ is the test-day milk yield in the last month of lactation and $\boldsymbol{D_{k+1}}$ is the interval between the date of the last test-day milk recorded and the date the cow was dried off (for cows with less than 305 d lactation) or the date the cow reached day 305 of lactation (for cows with longer than 305 d lactation). Differences between the predicted and actual lactation milk yields were analyzed to compare the accuracy of the prediction methods (IG, MIG, IP and the test-interval method) using a linear model that included the fixed effects of herd-year-season of calving, breed, parity and the prediction method as fixed effects, and the residual as a random effect. The least squares means were estimated and then were used to compare the predictive ability among the prediction methods.

Correlation analysis was studied between the predicted and actual lactation milk yields. The lactation milk yields predicted by the three functions used here, especially by IP, produced large negative or large positive values for some cows. If the differences between the predicted and actual lactation milk yields were above 15% or below -15% of the actual lactation milk yield of a cow, they were excluded from the analysis. Thus, about 8.7 % of the total 46,729 predicted lactation milk yields with the seven prediction methods were discarded from the analysis. Most discarded predicted records (83%) were those computed with IP fitted to both daily and monthly test-day milk data.

RESULTS AND DISCUSSION

Goodness of fit of the lactation curve functions

The herd-year-season of calving, parity, breed group of the cow, type of function, data type, data type × function and data type × function × breed interaction affected (P < 0.001) values of R^2 and adjusted R^2. The fitness of the three lactation curve functions was compared using the least squares means (LSM) of R^2 and adjusted R^2 (Table 1). The best fit function (the function that had the largest LSM of R^2 and adjusted R^2) to the daily and monthly test-day milk data was the MIG function and the poorest fit function was the IG function. The fitness of the MIG and IP functions obtained in this study was comparable based on the LSM of the R^2 values in other reports (Batra, 1986). The adjusted R^2 value for the IG function

(0.68) was lower than the one reported by Olori *et al*. (1999) for Holstein Friesian cows (0.944).

Wood's IG function is commonly used to fit milk data and as a basic reference in most model comparisons. However, its goodness of fit in the present and previous studies (Olori *et al*., 1999; Koonawootrittriron *et al*., 2001) was very poor. The R^2 value for the IG function in the present study was 0.71. This figure was lower than those obtained in the present study for the IP and MIG functions and by Olori *et al*. (1999) for the IG function, but it is comparable to the value (0.71) reported by Tekerli *et al*. (2000) for Friesian cows. Several modifications have been made to improve Wood's IG function (Perochon *et al*., 1996); some related to the functional form and mathematical properties of the function (Beever *et al*., 1991). The modified IG functions performed better than

Table 1 Least squares means (LSM) ± standard errors of R^2 and adjusted R^2 values.

Source of variation	LSM R^2	LSM adjusted R^2
Lactation curve function	$P = 0.0001$	$P = 0.0001$
Incomplete gamma (IG)	0.71 ± 0.002^{c}	0.68 ± 0.002^{c}
Modified incomplete gamma (MIG)	0.90 ± 0.002^{a}	0.89 ± 0.002^{a}
Inverse polynomial (IP)	0.89 ± 0.002^{b}	0.88 ± 0.002^{b}
Data type	$P = 0.0001$	$P = 0.0001$
Daily milk data (DD)	0.79 ± 0.002^{b}	0.79 ± 0.002^{b}
Monthly test-day milk data (MD)	0.88 ± 0.002^{a}	0.85 ± 0.002^{a}
Data type × lactation curve function	$P = 0.0001$	$P = 0.0001$
DD – IG	0.65 ± 0.002^{f}	0.64 ± 0.002^{e}
DD – MIG	0.88 ± 0.002^{c}	0.88 ± 0.002^{b}
DD – IP	0.85 ± 0.002^{d}	0.85 ± 0.002^{c}
MD - IG	0.79 ± 0.002^{e}	0.72 ± 0.002^{d}
MD – MIG	0.92 ± 0.002^{b}	0.91 ± 0.002^{a}
MD – IP	0.94 ± 0.002^{a}	0.91 ± 0.002^{a}
Breed group	$P = 0.0001$	$P = 0.0001$
Boran (B)	0.78 ± 0.003^{d}	0.74 ± 0.003^{d}
B × Friesian	0.86 ± 0.002^{a}	0.84 ± 0.002^{a}
B × Jersey	0.85 ± 0.003^{b}	0.83 ± 0.003^{ab}
B × Simmental	0.85 ± 0.004^{ab}	0.83 ± 0.004^{ab}
Horro (H)	0.86 ± 0.003^{a}	0.84 ± 0.003^{a}
H × Friesian	0.84 ± 0.003^{bc}	0.82 ± 0.003^{bc}
H × Jersey	0.83 ± 0.003^{c}	0.81 ± 0.003^{c}
H × Simmental	0.85 ± 0.004^{ab}	0.83 ± 0.004^{ab}
Parity	$P = 0.0001$	$P = 0.0001$
1	0.81 ± 0.002^{d}	0.79 ± 0.002^{d}
2	0.83 ± 0.002^{c}	0.81 ± 0.002^{c}
3	0.84 ± 0.002^{bc}	0.82 ± 0.002^{bc}
4	0.84 ± 0.002^{b}	0.82 ± 0.002^{b}
5	0.85 ± 0.002^{a}	0.83 ± 0.003^{a}
6	0.85 ± 0.003^{a}	0.83 ± 0.003^{a}
≥7	0.85 ± 0.003^{a}	0.83 ± 0.003^{a}

$^{a, b, c, d, e, f}$ = Least squares means within a column group with different superscript letters differ significantly ($P < 0.001$).

the IG function (Sherchand *et al*., 1995). The MIG function considered in the current study significantly ($P < 0.001$; Table 1) improved the goodness of fit of the IG function from 0.71 to 0.90. This improvement was observed in both daily and monthly test-day milk data. The better fit observed for the MIG and IP functions could be associated with the short ascending phase of the lactation curve in the studied herds (Gebregziabher *et al*., 2003). Batra (1986) indicated that the IP function had a good fit for lactations that started at a lower level and peaked earlier than average. Adediran *et al*. (2007) reported a poorer fit of the MIG function than of the IG function for test-day milk data for multiparous Holstein-Friesian cows. This difference could be related to the methodology used, as a non linear method was used to fit the function, or to other factors that affect the shape of the lactation curve.

The goodness of fit of these functions with monthly test-day was better than with daily milk data. The interaction of data type × function indicated that MIG function fitted to the daily milk data had the highest LSM of R^2 (0.88 ± 0.002; $P < 0.001$) and adjusted R^2 values (0.88 ± 0.002; $P < 0.001$). However, when the functions were applied to monthly test-day milk data, the IP function had the highest LSM of R^2 value (0.94 ± 0.002; $P < 0.001$), and LSM of adjusted R^2 values for the MIG and IP functions were not significantly different. The IG function had the lowest ($P < 0.001$) LSM of R^2 and adjusted R^2 values for both data types (Table 1). Differences in the fit of the functions by the type of data observed here were also reported in previous studies (Collins-Lusweti, 1991; Adediran *et al*., 2007).

The Horro and Boran × Friesian crosses had higher ($P < 0.001$) LSM of R^2 and adjusted R^2 than those of the other breed groups ($P < 0.001$, Table 1). Considering the LSM of R^2 values for the IG, MIG and IP functions fitted to the daily and monthly test-day milk data across breed groups (Figure 1), the goodness of fit of the MIG and IP functions was better than for the IG function. The MIG and IP functions had a similar goodness of fit across all breed groups for the monthly test-day milk data. However, for the daily milk data, the MIG function had a better fit ($P < 0.001$) than the IP function for the Boran and Horro groups, but the IP function had a better fit than the MIG function for the other breed groups (Figure 1). Differences in the goodness of fit of the lactation curve function among breed groups were reported by Alam *et al*. (2009). Koonawootrittriron *et al*. (2001) characterized four types of lactation curve of different breed groups and reported variations in the shape of the lactation curve among breed group × lactation × calving age subclasses, and breed group × lactation × calving season subclasses in a multibreed dairy herd in Thailand. Thus, the difference among breed groups could probably be associated with the differences in the shape of their lactation curves.

Milk data from cows in later parities (more than four parities) showed higher values for the LSM of R^2 ($P < 0.001$) and adjusted R^2 ($P < 0.001$) whereas first-parity cows showed the lowest values ($P < 0.001$). An increasing trend in the value of the LSM of R^2 with parity was observed in the present study. The difference between parities in goodness of fit could be related to differences in the initial milk yield, days to peak milk yield and persistency which determine the shape of the lactation curve and its fit. The first parity cows started lactation at a lower initial milk yield, required longer to reach their peak milk yield and were more persistent than cows in later parities. The better persistency of cows in the first parity could be related to the development of the udder and an increase in the size and number of milk-secreting cells. These differences create variations in the shape of the lactation curve and also in the fit of the lactation functions. Thus, comparisons among functions were reported for fitting best to lactations that started at a lower level and with fewer days to peak milk production (Batra, 1986).

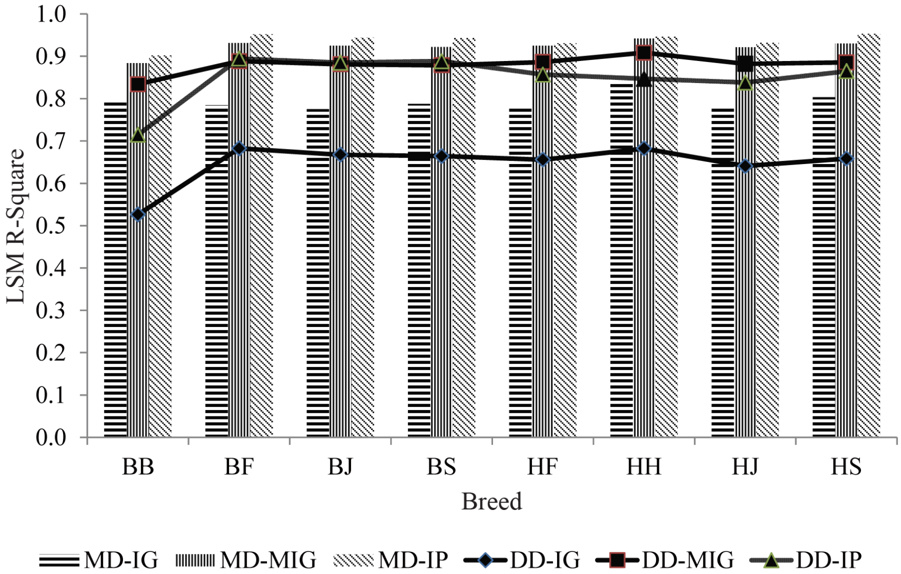

Figure 1 Least squares means (LMS) of correlation coefficient (R^2) for incomplete gamma (IG), modified incomplete gamma (MIG) and inverse polynomial (IP) functions fitted to daily (DD) and monthly test-day (MD) milk data across breed groups (H = Horro, B = Boran, BF = B × Friesian, HF = H × Friesian, BS = B × Simmental, HS = H × Simmental, BJ = B × Jersey, and HJ =H × Jersey).

The frequency distribution of the R^2 values across the different ranges of R^2 indicated that 52.1, 97.4 and 86.7% of the R^2 values for the IG, MIG and IP functions, respectively, fitted to daily milk data fell within the range of 0.8 to 1 and the corresponding figures for the monthly test-day milk data were 75.2, 98.0 and 97.8%, respectively (Figure 2). Silvestre *et al*. (2009) who classified $R^2 > 0.75$ as "best" fit and $R^2 \leq 0.75$ as "poor" fit, found 64.7% of their R^2 values were greater than 0.75. In the present study, 97.4% of the R^2 values for the MIG function and 86.7% of the R^2 values for the IP function fitted to the daily data and 98.0 and 97.8% for the monthly test-day milk data fell within the range 0.8 to 1.0 (Figure 2). With such frequency distributions of their R^2 values, the MIG and IP functions were the best fitting functions for the lactation pattern of the Ethiopian multibreed dairy cattle in this study.

Parameters of the best fit lactation curve functions

The comparison of the goodness of fit for the functions to the daily and monthly test-day milk data (Table 1) showed that the MIG function best fitted the daily milk data as it had the highest values for the LSM of R^2 (0.88 ± 0.002) and adjusted R^2 (0.88 ± 0.002). However, both the MIG and IP functions had similar values for the LSM of the adjusted R^2, but different values for the LSM of R^2 ($P < 0.001$) for the monthly test-day milk data. Further, the lactation milk yield prediction error from the monthly test-day milk data was the lowest for the MIG and IP functions (Table 3). Thus, they were selected to fit the monthly test-day milk data.

The parameters *ln(a)* and *c* of the MIG function from the daily and monthly test-day milk data, and A_0, A_1 and A_2 of the IP function from the monthly test-day milk data were different among breed groups ($P < 0.001$), parity ($P < 0.05$) and

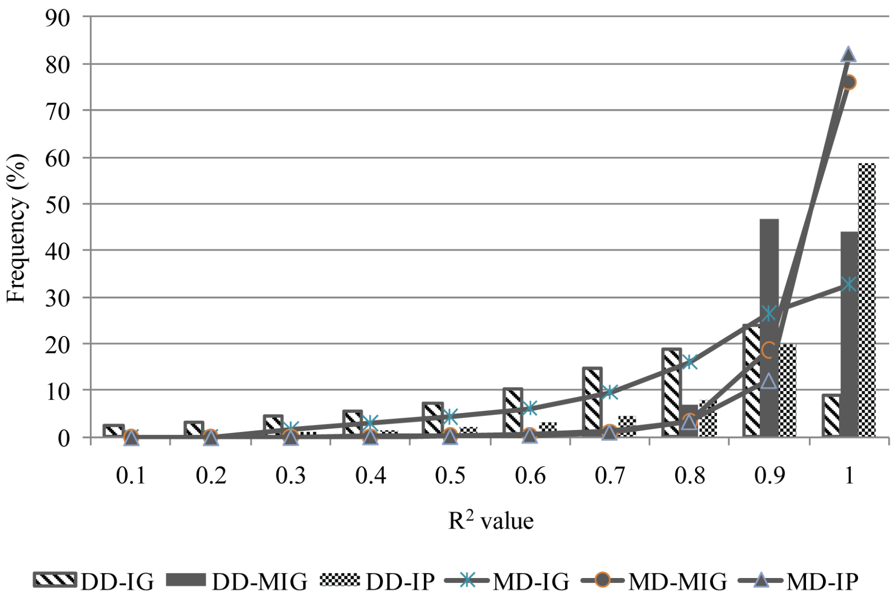

Figure 2 Frequency distribution of correlation coefficient (R^2) for incomplete gamma (IG), modified incomplete gamma (MIG) and inverse polynomial (IP) functions fitted to daily (DD) and monthly test-day (MD) milk data (values on X-axis are upper limits of the range).

herd-year-season ($P < 0.001$) subclasses. The lowest *ln(a)* and A_1 (average slope) and the highest *c*, A_0 (rate of increase to peak yield) and A_2 (rate of decline from peak yield) were recorded for the Horro and Boran cows. The parameters *ln(a), c,* A_0 and A_2 increased with parity (Table 2). The parameters *ln(a)* and *c* of the MIG function from the monthly test-day milk data were lower than the corresponding values from the daily milk data.

Different factors influence the shape of the lactation curve (Rekik and Gara, 2004). In particular, the shape of a lactation curve is affected by parameters of the function used for prediction (Silvestre *et al*., 2009). Breed group differences were observed in this study for the parameters *ln*(*a*) and *c* of the MIG function and for A_0, A_1 and A_2 of the IP function. Similar breed variations in the lactation function parameters were reported in other studies (Jenkins and Ferrell, 1992, Perochon *et al*., 1996, Horan *et al*., 2005). Perochon *et al*. (1996) estimated higher values for the parameter *ln*(*a*) in pure and crossbred Holstein than in Montbeliarde or French Friesian cows. The relatively better persistency of lactation, as indicated by lower values of *c* for crossbreds (HF, BF, HJ, BJ, HS and BS) than indigenous (Boran and Horro) cows, could be associated with the improvement in the overall dairy merit of the crosses (Demeke *et al*., 2003) as a result of additive and non-additive genetic effects. The parameters *ln*(*a*) and *c* of the MIG function and parameters A_0 and A_2 of the IP function increased with parity while the parameter A_1 decreased with parity (Table 2) indicating that first-lactation cows had lower and flatter lactation curves than later-lactation cows (Batra 1986; Collins-Lusweti, 1991; Koonawootrittriron *et al*., 2001; Horan *et al*., 2005). The parameter *c* is a positive parameter (Rekik and Gara, 2004) in a typical lactation curve and its inverse explains the persistency of lactation. Thus, lower values of *c* (rate of decline from peak) are related to cows having relatively more persistent lactation. The parameter *c* of the MIG function showed an increasing trend with parity indicating better lactation persistency of first-parity cows compared to later-parity cows.

Table 2 Least squares means ± standard errors of parameters of modified incomplete gamma (MIG) function and inverse polynomial (IP) function.

	MIG – daily		MIG - monthly test-day		IP - monthly test-day		
	ln(a)	*c*	*ln(a)*	*c*	A_0	A_1	A_2
Breed	P = 0.0001	P = 0.0001	P = 0.0001	P = 0.0001	P = 0.0001	P = 0.0001	P = 0.0001
Boran (B)	-2.16 ± 0.020^{e}	0.0166 ± 0.0002^{a}	-2.30 ± 0.021^{e}	0.0154 ± 0.0002^{a}	60.6 ± 3.39^{a}	-1.221 ± 0.087^{b}	0.011 ± 0.0006^{a}
B × Friesian	-1.09 ± 0.013^{a}	0.0132 ± 0.0001^{bc}	-1.32 ± 0.014^{a}	0.0118 ± 0.0001^{bc}	10.0 ± 2.10^{c}	-0.117 ± 0.054^{a}	0.001 ± 0.0003^{b}
B × Jersey	-1.30 ± 0.017^{bc}	0.0129 ± 0.0002^{bc}	-1.52 ± 0.019^{bc}	0.0116 ± 0.0002^{bc}	8.7 ± 2.84^{c}	-0.115 ± 0.073^{a}	0.002 ± 0.0005^{b}
B × Simmental	-1.26 ± 0.025^{b}	0.0124 ± 0.0003^{c}	-1.48 ± 0.027^{b}	0.0112 ± 0.0003^{c}	7.7 ± 4.12^{c}	-0.073 ± 0.111^{a}	0.002 ± 0.0007^{b}
H × Friesian	-1.25 ± 0.020^{b}	0.0136 ± 0.0002^{b}	-1.47 ± 0.021^{b}	0.0123 ± 0.0002^{b}	16.9 ± 3.24^{c}	-0.297 ± 0.087^{a}	0.003 ± 0.0005^{b}
Horro (H)	-1.73 ± 0.022^{d}	0.0174 ± 0.0003^{a}	-1.95 ± 0.024^{d}	0.0159 ± 0.0002^{a}	36.5 ± 3.70^{b}	-0.814 ± 0.095^{b}	0.009 ± 0.0006^{a}
H × Jersey	-1.37 ± 0.022^{c}	0.0132 ± 0.0003^{bc}	-1.60 ± 0.023^{c}	0.0119 ± 0.0002^{bc}	20.1 ± 3.60^{c}	-0.348 ± 0.092^{a}	0.003 ± 0.0006^{b}
H × Simmental	-1.33 ± 0.028^{bc}	0.0130 ± 0.0003^{bc}	-1.55 ± 0.029^{bc}	0.0117 ± 0.0003^{bc}	4.7 ± 4.52^{c}	0.029 ± 0.120^{a}	0.001 ± 0.0007^{b}
Parity	P = 0.0001	P = 0.0001	P = 0.0001	P = 0.0001	P = 0.0094	P = 0.0004	P = 0.0165
1	-1.69 ± 0.012^{e}	0.0131 ± 0.0001^{d}	-1.90 ± 0.013^{d}	0.0117 ± 0.0001^{d}	14.0 ± 2.02^{b}	-0.162 ± 0.052^{a}	0.003 ± 0.0003^{b}
2	-1.50 ± 0.013^{d}	0.0135 ± 0.0001^{cd}	-1.71 ± 0.014^{c}	0.0122 ± 0.0001^{cd}	18.0 ± 2.13^{a}	-0.289 ± 0.055^{ab}	0.003 ± 0.0004^{a}
3	-1.42 ± 0.014^{c}	0.0140 ± 0.0002^{bc}	-1.63 ± 0.015^{b}	0.0128 ± 0.0002^{b}	21.5 ± 2.30^{a}	-0.409 ± 0.059^{b}	0.004 ± 0.0004^{a}
4	-1.40 ± 0.015^{bc}	0.0139 ± 0.0002^{bc}	-1.61 ± 0.016^{ab}	0.0126 ± 0.0002^{bc}	22.8 ± 2.50^{a}	-0.420 ± 0.064^{b}	0.004 ± 0.0004^{a}
5	-1.34 ± 0.018^{ab}	0.0143 ± 0.0002^{ab}	-1.55 ± 0.019^{a}	0.0131 ± 0.0002^{ab}	21.4 ± 2.88^{a}	-0.367 ± 0.074^{ab}	0.004 ± 0.0005^{a}
6	-1.38 ± 0.021^{abc}	0.0143 ± 0.0002^{ab}	-1.60 ± 0.022^{ab}	0.0130 ± 0.0002^{ab}	21.0 ± 3.41^{a}	-0.414 ± 0.087^{b}	0.004 ± 0.0006^{a}
≥7	-1.32 ± 0.020^{a}	0.0151 ± 0.0002^{a}	-1.54 ± 0.021^{a}	0.0138 ± 0.0002^{a}	25.8 ± 3.31^{a}	-0.526 ± 0.085^{b}	0.005 ± 0.0005^{a}

a, b, c, A_0, A_1, A_2 = Parameters of the functions.

$^{a, b, c, d, e}$ = Least squares means within a column group with superscript different letters differ significantly ($P < 0.001$).

According to Horan *et al*. (2005), their comparison of cows from three parity groups indicated that third parity cows had the highest initial milk yield, the greatest increase in milk yield between calving and peak milk production, and the greatest rate of milk yield decline between peak production and the end of the lactation. Conversely, primiparous cows had the lowest initial milk yield, the least increase in milk yield between calving and peak milk production, and the least decline in milk production from peak milk production to the end of lactation (Horan *et al*., 2005). Collins-Lusweti (1991) associated the effect of parity on the shape of the lactation curve to differences in the rate of depletion of body reserves. Mature cows use their body reserves much faster in the early stages of lactation which leads to higher values of b and c than in heifers (Collins-Lusweti, 1991). The udder of first-lactation cows is still undergoing a maturation process that leads to an increase in milk secreting cells as lactation progresses which counterbalances the normal decline in milk yield compared to multiparous cows (Stanton *et al*., 1992). Stanton *et al*. (1992) tried to relate the age effect on test-day to identify the reason for the better lactation persistency of first-parity cows and found that the age effect became more positive as the first lactation progressed.

Prediction of lactation milk yields

Analysis of the difference between the predicted and actual lactation milk yield showed significant differences among the prediction methods, breed, herd-year-season of calving and parity ($P < 0.001$; Table 3) subclasses. Differences between the predicted and actual lactation milk yields were different from zero, indicating that the four functions (that is, MIG, IP, IG and the test-interval method) predicted lactation milk yields with different prediction errors. Different studies (for example, Congleton and Everett, 1980;Tozer and Huffaker, 1999; Koonawootrittriron *et al*., 2001; Berry *et al*., 2005) indicated the possibility of predicting the lactation milk yield from daily or test-day milk data using the lactation curve function or the test-interval method. However, based on the LSM of prediction errors, better predictions were obtained from the monthly test-day milk data than from the daily milk data for all functions ($P < 0.001$). This result contradicts Congleton and Everett (1980), who reported that the errors of prediction for cumulative lactation milk yield using the IG function fitted with monthly test-day milk data were higher than those fitted with the daily milk data.

The MIG function, IP function, test-interval method and IG function ranked from first to fourth, respectively, when predicting the lactation milk yield from the monthly test-day milk data. The lactation milk yield predicted from the daily milk data showed higher prediction errors for all functions with the IG function (-15.56 ± 0.89 kg) having a comparatively lower prediction error than the MIG function (52.8 ± 0.89 kg) and the IP function (-28.75 ± 1.01 kg).

The LSM of the difference between the predicted and actual lactation milk yield for Boran × Simmental, Horro, Horro × Jersey and Horro × Simmental was very low compared to the other breed groups (Table 3). The function underpredicted the lactation milk yield for Boran and overpredicted for Horro × Friesian cows. Comparisons among the different parities indicated that the functions predicted the lactation milk yield with the LSM prediction error ranging from -1.46 to 3.42 kg.

In addition to prediction methods, variation in the LSM of the differences between the predicted and actual milk yields were associated with differences in herd-year-seasons, parities and breed groups of cows. The MIG function fitted to the monthly test-day milk data improved ($P < 0.001$) the accuracy of prediction relative to the test-interval method. The prediction error for the MIG function (4.19 ± 0.91 kg) was smaller than that of the test-interval method (-9.48 ± 0.90 kg).

Table 3 Least squares means and standard errors of the differences (LSMD) and correlations (r) between predicted and actual lactation milk yield.

	Number of records	LSMD (kg)	r*
Prediction method		P = 0.0001	
IG-daily	6,670	-15.56 ± 0.89[e]	0.999 ± 0.0002
IG- Monthly test-day	6,434	10.91 ± 0.91[b]	0.998 ± 0.0010
MIG-daily	6,670	52.80 ± 0.89[a]	0.998 ± 0.0003
MIG-monthly test-day	6,406	4.19 ± 0.91[c]	0.997 ± 0.0010
IP-daily	4,943	-28.75 ± 1.01[f]	0.999 ± 0.0010
IP-Monthly test-day	4,973	-7.25 ± 1.01[d]	0.998 ± 0.0020
Test interval method	6,548	-9.48 ± 0.90[d]	0.998 ± 0.0010
Parity		P = 0.0008	
1	10,453	1.06 ± 0.78[ab]	
2	8,794	0.02 ± 0.82[ab]	
3	7,192	2.00 ± 0.88[ab]	
4	5,773	-1.46 ± 0.96[b]	
5	4,175	3.42 ± 1.11[a]	
6	2,937	-1.27 ± 1.31[ab]	
≥7	3,320	3.09 ± 1.27[ab]	
Breed		P = 0.0001	
Boran (B)	3,681	-6.10 ± 1.32[c]	
B × Friesian	18,044	3.00 ± 0.81[ab]	
B × Jersey	5,244	3.15 ± 1.10[ab]	
B × Simmental	2,023	2.52 ± 1.59[ab]	
H × Friesian	3,691	5.21 ± 1.26[a]	
Horro (H)	5,336	-1.18 ± 1.42[bc]	
H × Jersey	2,878	0.82 ± 1.40[ab]	
H × Simmental	1,747	0.42 ± 1.73[abc]	

IG = incomplete gamma function, MIG = modified incomplete gamma function, IP = inverse polynomial function.

[a, b, c, d, e, f] = Least squares means within a column group with different superscript letters differ significantly (P < 0.001).

* = Correlation between actual lactation milk yield and milk yield predicted using the seven prediction methods (all correlation coefficients were significant, P < 0.001)

Congleton and Everett (1980) reported that when IG curves were fitted to monthly observations of daily milk production over the entire 305 d lactation, the error of prediction of the 305 d cumulative yield (183.5 kg) was comparable to the prediction errors of test-interval methods. Tozer and Huffaker (1999) reported that the IG and IP functions overestimated the lactation milk yield for all lactations by less than 5% for all functions and parities. In the present study, the prediction from the IG function fitted to monthly test-day data differed significantly (P < 0.001) in value and sign from the test-interval method. The IG function overpredicted (10.91 ± 0.91 kg) while the test-interval method underpredicted (-9.48 ± 0.90 kg) the lactation milk yield.

The lactation curves of the daily milk yield predicted from function parameters estimated from fitting the modified incomplete gamma (MIG) to the daily and monthly test-day data and the inverse polynomial function to the monthly test-day data showed that the lactation curve from the MIG function had higher values of predicted daily milk yield throughout lactation (Figure 3). In addition, the lactation curve for the daily milk yield predicted from function parameters of the MIG function fitted to the daily milk data had higher values than those from the monthly test-day milk data.

The correlation between the lactation milk yield predicted by the different prediction methods with the actual lactation milk yield ranged from 0.997 to 0.999 (Table 3). The high correlation between the predicted and actual lactation milk yield obtained for all prediction methods (from 0.997 to 0.999) here agrees with Naranchuluum *et al*. (2011) who reported a correlation coefficient of 0.98.

CONCLUSION

Three lactation curve functions were compared for their goodness of fit to daily and test-day milk data. The MIG function had the best fit to the daily milk data, while both the MIG and IP functions had similar goodness of fit to the monthly test-day milk data. The goodness of fit of the functions was different among breeds, parities and data types. The parameters of the lactation curve functions were affected by the herd-year-season of calving, breed and parity of cows. The lactation milk yield was better predicted by functions fitted to the monthly test-day milk data and the test-interval method. The MIG function predicted the lactation milk yield from the monthly test-day milk data with a lower prediction error than the other functions fitted to the monthly test-day milk data. The functions in this dataset that had the best fit could potentially be used in test-day-based genetic models for future genetic evaluations of Ethiopian cattle.

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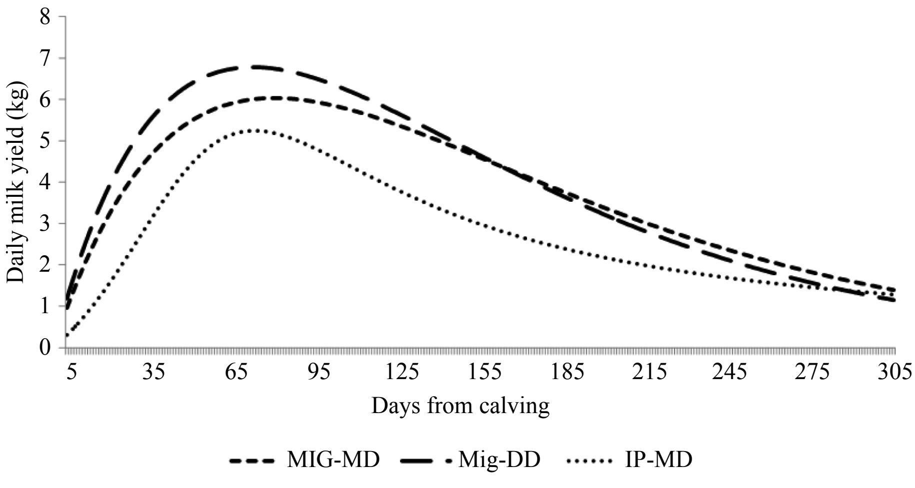

Figure 3 Lactation curves of daily milk yield predicted from function parameters estimated from fitting the modified incomplete gamma (MIG) function to daily (MIG-DD) and monthly test-day (MIG-MD) data and inverse polynomial (IP) function to monthly test-day (IP-MD) data.

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