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Growth curve of dairy artificial insemination bulls raised under Thai tropical conditions

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Abstract

The growth curve of dairy artificial insemination bulls was evaluated under Thai tropical conditions. Data consisted of 4,963 monthly body weights from 140 bulls collected from 1996 to 2015 at the Semen Production and Dairy Genetic Evaluation Center of the Dairy Farming Promotion Organization of Thailand. Four breed groups were defined based on their Holstein (H) fraction: BG1 ($0.96 \leq H \leq 1.00$), BG2 ($0.91 \leq H < 0.96$), BG3 ($0.86 \leq H < 0.91$) and BG4 ($0.44 \leq H < 0.86$). Linear (Quadratic) and nonlinear (Gompertz, Logistic, Von Bertalanffy and Brody) models were compared for goodness of fit using -2logL, Akaike information criterion (AIC), corrected AIC (AICC) and Bayesian information criterion (BIC). The Quadratic model had lowest values for these four criteria. Predicted weights at ages 30 mo and 60 mo were higher for bulls in BG2 than bulls in BG1, BG3 and BG4. Growth curves from these bulls would be useful to identify sires expected to produce steers with faster growth rates and heifers with younger ages at first calving. Unfortunately, weights from steer and heifer progeny from these bulls were unavailable. Consequently, progeny weights would need to be collected if genomic selection for growth traits were to be implemented in the Thai multibreed population.

Introduction

Knowledge of growth patterns in cattle is important for making appropriate herd management, nutrition and selection decisions aimed at improving beef production efficiency (Menchaca et al., 1996; Goldberg and Ravagnolo, 2015). Although beef steers supply the majority of beef in Thailand, dairy steers are also fattened to cover beef shortages, to stabilize prices of beef products, and to provide a choice to consumers demanding high quality beef (Osothongs et al., 2016; Pluemjai et al., 2016). Unfortunately, there is currently no information available on growth patterns and slaughter ages of dairy steers in either farms or feedlots in Thailand. However, weight data exists on Holstein (H) and Holstein crossbred bulls belonging to the Semen Production and Dairy Genetic Evaluation Center of the Dairy Farming Promotion Organization of Thailand (DPO) from near birth to age 8 yr. These data could be used to gain knowledge on expected growth curves of their progeny fed on their own farms of origin or in feedlots as well as insights on the expected mature weight of their daughters in dairy farms.

Most cattle in the Thai dairy multibreed population have a high H percentage with various fractions of other *Bos taurus* (Brown Swiss, Jersey, Red Dane) and (or) *Bos indicus* (Brahman, Red Sindhi, Sahiwal, Thai Native) breeds (Koonawootrittriron et al., 2009). Knowledge of growth curves of artificial insemination sires of

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various H fractions at the DPO would help to identify sires whose steer progeny would be expected to have faster growth rates and shorter fattening times and whose daughters would be of moderate mature size. This would help improve genetic selection for growth and dairy production efficiency, which in turn would be expected to increase farm profitability. A variety of mathematical models can be used to analyze growth curves as well as to predict body weight from partial records including Brody (Brody, 1945), Von Bertalanffy (Von Bertalanffy, 1957), Logistic (Nelder, 1961), Gompertz (Gompertz, 1825) and polynomial regression model. Thus, the objective of this research was to evaluate the growth curve of bulls from the DPO to obtain insights on expected slaughter age of steer progeny of various H percentages and on the expected mature weights of their daughters using five mathematical models (Quadratic, Logistic, Gompertz, Von Bertalanffy, Brody).

Materials and Methods

Animals and data

In total, 140 bulls from the Semen Production and Dairy Genetic Evaluation Center of the DPO were used in this research. These bulls were the progeny of 55 sires and 136 dams. The DPO personnel chose potential sires and dams of bulls based on Expected Progeny Differences (EPD) for milk production. Sires of bulls belonging to the Semen Production and Dairy Genetic Evaluation Center of the DPO and dams of bulls were from 59 dairy farms in Central, Northern, Northeastern, and Southern Thailand. Bulls were raised under the same nutritional regimen, management and health care at the Semen Production and Dairy Genetic Evaluation Center of the DPO located in Muaklek, Saraburi province, Thailand, (14º38´24.7″N; 101º11´57.2″E).

The Thai multibreed population is the product of an upgrading process from various *Bos indicus* and *Bos taurus* breeds to Holstein. Breeds represented in the multibreed dairy population were Holstein, Brahman, Jersey, Red Dane, Red Sindhi, Sahiwal and Thai Native. Ninety-four percent of the bulls in this population were H crossbreds, and the remaining 6% were purebred H. The average H fraction of bulls was 92.5% (minimum = 44%; maximum = 100%). Four breed groups were constructed based on the H percentage of the bulls in the population: BG1 ($0.96 \leq H \leq 1.00$), BG2 ($0.91 \leq H < 0.96$), BG3 ($0.86 \leq H < 0.91$) and BG4 ($0.44 \leq H < 0.86$). Numbers of animals per breed group and total, numbers of records per breed group and total, and number of records per animal per breed group and total are shown in Table 1.

Table 1 Number of animals, number of records and number of records per animal per breed group and total

Breed group	Number of animals	Number of records	Number of records per animal
BG1	63	2276	36
BG2	34	1300	38
BG3	24	767	32
BG4	19	620	33
Total	140	4963	36

BG1 = $0.96 \leq H \leq 1.00$; BG2 = $0.91 \leq H < 0.96$; BG3 = $0.86 \leq H < 0.91$; BG4 = $0.44 \leq H < 0.86$, where H = Holstein fraction.

The dataset consisted of monthly body weights (n = 4,963) from 140 dairy bulls born from 1996 to 2015. Bulls were weighed monthly starting from birth until a bull completed 25,000 doses of frozen semen or when a bull was aged approximately 96 mo. Monthly body weights of bulls younger than age 5.5 mo and older than 96 mo were excluded from the analysis because of missing or erroneous information or both.

Climate, housing and management

The weather characteristics in Central Thailand are influenced by tropical monsoons, with the Southwest monsoon from May to October and the Northeast monsoon from October to February. Temperatures in this region during the years of the study (1996–2015) ranged from 15 °C to 34 °C, the relative humidity (RH) fluctuated between 33% and 97%, and the average rainfall was 1,113 mm/yr. Based on Thai Meteorological Department (2015), seasons were classified as winter (November–February; 14.5–31.6 °C, 65% RH, 50 mm rain/season), summer (March–June; 20.8–34.2 °C, 72% RH, 339 mm rain/season), and rainy (July–October; 23.2–31.8 °C, 77% RH, 724 mm rain/season).

Bulls were raised in open barns. Each bull was kept in a 4 m ×22 m stall with a raised area and an exercise area. The raised area was 4 m × 6 m, with a concrete floor and a tiled roof (2.5–3 m high). The exercise area was 4 m × 16 m, with a dirt floor and no roof. Feed and water bunks were located in the front of the stall. Bulls were kept in their stalls at all times, except when semen was collected.

Bulls were fed 4–6 kg/d of concentrate (14–16% crude protein) and had free access to fresh roughage, water and a mineral supplement throughout the year. The concentrate was purchased from a local company (Charoen Pokphand Foods, Bangkok, Thailand) and its ingredients included protein sources (palm meal, soybean meal, cotton seed meal, leucaena), energy sources (cassava, rice bran, broken rice, fat from animals and plants, molasses), and mineral and vitamin sources (di-calcium, premixes). Fresh roughage consisted of Guinea (*Panicum maximum*), Ruzi (*Brachiaria ruziziensis)*, Napier (*Pennisetum purpureum*), and Para (*Brachiaria mutica*) grasses cut and carried to the bull stalls. Bulls were also given Guinea and Ruzi grass hay and silage during the dry season (November–March) when fresh grass was scarce. Lastly, bulls were vaccinated against foot and mouth disease, tuberculosis , and were dewormed every 6 mo.

Statistical analysis

Bull growth data were analyzed using the five models in Equation 1–5: Quadratic

$$y_t = b_0+b_1t+b_2t^2+e_t \quad (1)$$

Gompertz (Gompertz, 1825)

$$y_t = A\ exp\ (-B\ exp(-kt)) + e_t \quad (2)$$

Logistic (Nelder, 1961)

$$y_t = A\ (1+B\ exp(-kt))^{-1} + e_t \quad (3)$$

Von Bertalanffy (Von Bertalanffy, 1957)

$$y_t = A\ (1-B\ exp(-kt))^3 + e_t \quad (4)$$

Brody (Brody, 1945)

$$y_t = A\ (1-B\ exp(-kt)) + e_t \quad (5)$$

where y_t is the body weight (measured in kilograms) at age t (in months) corrected by contemporary group (year-month of birth) and heterosis fixed effects, b_0 is the initial body weight, b_1 is the linear regression coefficient, b_2 is the Quadratic regression coefficient, A is the asymptotic mature weight, B is the degree of maturity at birth, k is the maturing rate, and e_t is the residual. Eq. (1) was analyzed using the mixed procedure of SAS (SAS, 2011), whereas the models in Eq. (2)–(5) were analyzed using the NLMIXED procedure of SAS.

Goodness of fit for the five models was assessed using four fit statistics: 1) -2logL, where logL is the natural logarithm of the likelihood function; 2) Akaike information criterion (AIC) = -2logL + 2k, where k is the number of parameters (Akaike, 1974); 3) corrected Akaike information criterion (AICC; Burnham and Anderson, 1998) = -2logL + 2kn / (n - k - 1), where, n is the number of observations and k is the number of parameters; and 4) Schwarz Bayesian information criterion (BIC; Schwarz, 1978) = -2logL + klog(n). The model with the smallest -2logL, AIC, AICC and BIC values was chosen to be the best for fitting bull growth curves in this population. The chosen model was used to compute parameters for each of the four breed groups of bulls. Parameters for each breed group were used to compute weights at various ages to plot growth curves for the four breed groups.

Results and Discussion

Growth data

Fig.1 shows a scatter plot of weights from all bulls collected at ages in the range 5.5–96 mo. The average number of weighings per bull was 35.6 (SD = 20.2). The scatter plot shows that bull growth followed a relatively straight path until age approximately 60 mo, after which it plateaued. These bull weight data can be utilized to obtain some information on the growth patterns of their steer progeny fed for beef (first 30 mo of age) and of their daughters reared as replacement dairy cows (all months). The weights in Fig.1 could be divided into three phases: 1) early growth, from age 5.5 mo to 30 mo; 2) late growth, from age 30 mo to 60 mo; and 3) maturity, after age 60 mo. The body weight fluctuated depending on environmental factors (climate, nutrition, health). These phases will be considered in the discussion of prediction models for bull growth and predicted growth curves for animals of four breed groups in the Thai multibreed population.

Overall goodness of fit of growth models

Table 2 contains the values of the four goodness of fit statistics used to compare the five models used in this study. The Quadratic model had the smallest -2LogL, AIC, AICC, and BIC values; thus it best fitted the growth data from age 5.5 mo to 96 mo. Model rankings were identical for -2LogL, AIC, and AICC in all five models, and these rankings were the same to those of BIC where the Quadratic model was first and the Brody model was fifth. Values of AIC, AICC and BIC differed because of the values of the adjustment factors applied to -2LogL. The AIC adjusts -2LogL by adding a penalty of twice the number of parameters involved in each model (2k), and AICC adjusts -2LogL for the number of parameters k and the sample size n (2kn/(n - k - 1). Thus, for large samples (where n is large), the AICC correction approaches 2k, and AICC approaches AIC and consequently both will tend to select the same model (Lee and Ghosh, 2009). Conversely, BIC includes a value of total model parameters multiplied by the natural logarithm of total records (klog(n)), which will increase as n increases, hence it is a more stringent statistic than AIC and AICC (Cobuci et al., 2011; Dziak et al., 2012).

No previous growth curve studies including the Quadratic and the four nonlinear models considered here (Gompertz, Brody, Von Bertalanffy, Logistic) were found in the literature. Among the nonlinear models, the Von Bertalanffy model was found to provide a better fit for growth curves than Gompertz, Logistic, Brody, and Richards in Holstein females (Berry et al., 2005). The Von Bertalanffy model also fitted growth better in the group of Holstein, Ayrshire

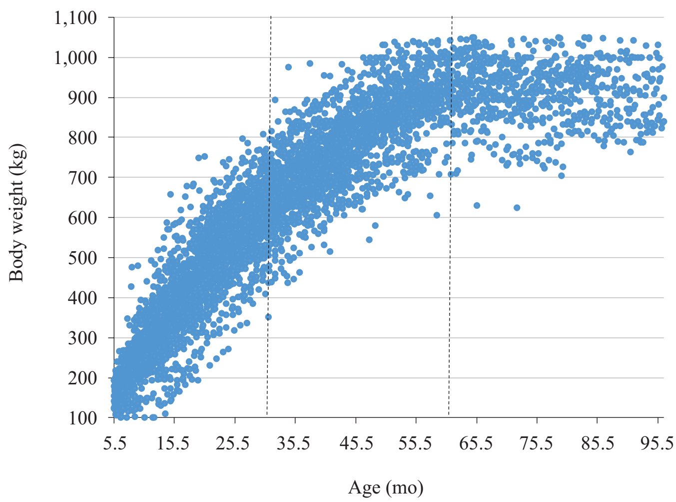

Fig. 1 Scatter plot of bull weights from age 5.5 mo to 96 mo

Table 2 Comparison of growth models using -2log Likelihood (-2logL), Akaike information criterion (AIC), corrected Akaike information criterion (AICC), and Schwarz Bayesian information criterion (BIC)

Model	-2logL	AIC	AICC	BIC
Quadratic	54068	54070	54070	54076
Logistic	54097	54105	54105	54131
Gompertz	54101	54109	54109	54135
Von Bertalanffy	54131	54139	54139	54165
Brody	54306	54314	54314	54340

and Holstein-Ayrshire crossbred females than the Gompertz and Logistic models, which tended to overestimate early weights and to underestimate mature weights (Perotto et al., 1992; García-Muñiz et al., 1998). However, the Brody model fitted the growth curve of Jersey cows better than the Logistic, Von Bertalanffy, and Gompertz (Brown et al., 1976), although the best model occurred with the Richards function (Richards, 1959). In beef cattle, the Von Bertalanffy model fitted the growth curve of Spanish Retinta beef cows better than the Brody model (López de Torre et al., 1992). Conversely, the Brody model provided a better fit to the growth curve of Nellore cattle than the Gompertz and Von Bertalanffy models (Forni et al., 2009), for Hereford and Charolais-Angus-Galloway crossbred cattle than the Logistic and Von Bertalanffy models (Goonewardene et al., 1981) and for Hereford and Brahman-Hereford crossbreds than the Logistic, Von Bertalanffy and Gompertz models (Brown et al.,1976). However, the Richards model (Richards, 1959) produced the best growth curve fit in Brown et al. (1976) and Goonewardene et al. (1981). Clearly, no single growth function provided a uniformly better fit across studies involving a variety of dairy and beef cattle breeds. In addition to the genetic composition of cattle and environmental conditions (management, nutrition, climate, health conditions), sample size may also have contributed to differences among models. Thus, although the Quadratic model was found to fit the growth of dairy bulls aged between 5.5 mo and 96 mo better than the other four models with the currently available data, this outcome may change in the future as additional data are collected.

Predicted growth curves by growth phase

Table 3 presents estimates of parameters and the SE for the five models in this study, and Fig. 2 shows the corresponding bull growth curves predicted using these parameters. The plot of actual weights over age (Fig. 1) showed that the body weight of bulls in this study increased until they reached maturity at age approximately 60 mo, then bull weights fluctuated and appeared to slightly decrease until age 96 mo. The shapes of the growth curves for the five models were similar during early and late growth, but differed at maturity. All models tended to fit growth in the early and late growth periods well. However, mature weights tended to be underestimated by the Quadratic model and overestimated by the four nonlinear models.

A description of the predictive ability of the five models during the three growth stages is shown in Table 4 in terms of means and SD of differences between the predicted and actual body weights during early growth, late growth and at maturity. The Logistic model generated the largest differences between the predicted and actual weights for all models in early growth, whereas the Brody model generated the largest differences between predicted and actual weights for late growth and at maturity. The Quadratic and Von Bertalanffy models tended to slightly overestimate bull weights during early growth (Quadratic, 2.67; Von Bertalanffy, 0.45), underestimate weights during late growth (Quadratic, -1.64; Von Bertalanffy, -4.94), and overestimate weights at maturity (Quadratic: 7.53, Von Bertalanffy, 10.63). The Logistic model overestimated weights during early growth (13.31), slightly underestimated weights during late growth (-0.51) and overestimated weights at maturity (11.84) more than the other models, except Brody. The Gompertz model tended to underestimate weights during early growth (-1.50) and late growth (-3.59) and to overestimate weights at maturity (7.09). The Brody model overestimated weights during early growth (4.66), underestimated weights during late growth (-11.39) and grossly overestimated weights at maturity (18.06), producing the worst fit of all the models in late growth and at maturity. Considering the simplicity of the Quadratic model and the reasonably small differences in all growth phases, this model was preferred to the nonlinear models for genetic or genomic evaluation of growth traits in the Thai dairy multibreed population, particularly if applied using Legendre polynomials or splines.

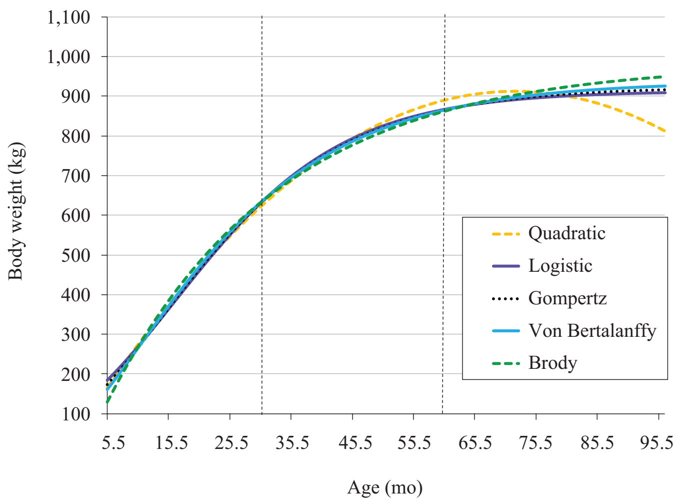

Fig. 2 Predicted growth curves between age 5.5 mo and 96 mo using five growth models

Table 3 Parameter values ± SE by growth model

Model	Parameter[a]					
	b_0	*p*-Value	b_1	P-value	b_2	*p*-Value
Quadratic	37.77 ± 3.46	0.0001	24.25 ± 0.18	0.0001	-0.1681 ± 0.0021	0.0001
	A		B		K	
Logistic	912.92 ± 3.36	0.0001	0.0671 ± 0.0007	0.0001	3.0427 ± 0.0302	0.0001
Gompertz	923.31 ± 3.63	0.0001	2.3134 ± 0.0251	0.0001	0.0592 ± 0.0007	0.0001
Von Bertalanffy	937.04 ± 3.98	0.0001	0.5887 ± 0.0053	0.0001	0.0513 ± 0.0006	0.0001
Brody	982.73 ± 5.34	0.0001	1.0556 ± 0.0063	0.0001	0.0354 ± 0.0005	0.0001

b_0 = initial body weight; b_1 = linear regression coefficient; b_2 = Quadratic regression coefficient; A = asymptotic mature weight; B = degree of maturity at birth; K = maturing rate.

Table 4 Means and SD of differences between predicted and actual body weights by growth period

Model	Early growth		Late growth		Maturity	
	Mean	SD	Mean	SD	Mean	SD
Quadratic	2.67	71.66	-1.64	75.43	7.53	62.99
Logistic	13.31	84.12	-0.51	76.26	11.84	67.74
Gompertz	-1.50	71.07	-3.59	76.31	7.09	62.32
Von Bertalanffy	0.45	71.07	-4.94	76.45	10.63	63.20
Brody	4.66	71.93	-11.39	76.69	18.06	66.15

To analyze the mean growth performance for the set of bulls in the study, the weights at ages 5.5 mo, 30 mo and 60 mo were predicted using the best model (Quadratic). The predicted weights based on the Quadratic model indicated that the mean bull weight increased by an average of 445 kg during the early growth period (168 kg at 5.5 mo to 613 kg at 30 mo) and by 274 kg during the late growth period (613 kg at 30 mo to 887 kg at 60 mo). This indicated a decrease in the growth rate of 62% between early and late growth. A similar pattern of growth was found in US Holstein (Calo et al., 1973), where the bull weight increased by 599 kg during early growth (218 kg at 6 mo to 817 kg at 30 mo) and by 197 kg (817 kg at 30 mo to 1014 kg at 60 mo) during late growth, a decrease of 33% in their growth rate. Bull weights after age 60 mo fluctuated around their mature weight because the feeding objective was to provide them with enough food to be in appropriate condition for artificial insemination. The pattern of growth observed in bulls from the Thai multibreed population reflected the typical cattle growth curve where there is an acceleration phase, then a point of inflection between early and late growth where the rate of growth decreases steadily until reaching maturity where bull weight remains relatively constant over time.

Predicted growth curves by breed group

Quadratic regression coefficients were estimated for animals in each of the four breed groups specified according to their breed composition (Table 5). These within-breed group Quadratic regression coefficients were used to compute predicted values for each animal at every age in all four breed groups. A description of the predicted ability of the Quadratic model in terms of means and SD of differences between predicted and actual weights in each growth period for each breed group and the complete dataset are presented in Table 6. The Quadratic model underestimated BG2 weights in all growth phases, tended to overestimate BG3 and BG4 weights and yielded the closest predictions during early and late growth for BG1 than for any other breed group. Bull predicted weights were subsequently plotted against age to construct growth curves for the four breed groups (Fig. 3). The predicted weights of bulls in BG2 were higher than those from BG1, BG3 and BG4 during the early growth period (age 5.5 mo to 30 mo) and the late growth period (age 30 mo to 60 mo). The rate of growth of BG3 and BG4 bulls until age 60 mo was lower than that of BG1 and BG2 resulting in weights at age 60 mo that were approximately 25 kg lower than those of BG1 and BG2. The predicted weights of bulls at maturity tended to be higher for BG2 and BG3 than BG1 and BG4.

Table 5 Coefficient of regression estimates ± SE for the Quadratic model by breed group

Breed group	Coefficient of regression					
	b_0	p-Value	b_1	p-value	b_2	p-Value
BG1	38.027 ± 5.159	0.0001	24.586 ± 0.289	0.0001	-0.174 ± 0.003	0.0001
BG2	38.481 ± 5.645	0.0001	24.956 ± 0.307	0.0001	-0.175 ± 0.003	0.0001
BG3	34.495 ± 11.024	0.0018	22.574 ± 0.549	0.0001	-0.143 ± 0.005	0.0001
BG4	23.923 ± 8.661	0.0059	24.538 ± 0.470	0.0001	-0.174 ± 0.004	0.0001

BG1 = 0.96 ≤ H < 1.00; BG2 = 0.91 ≤ H < 0.96; BG3 = 0.86 ≤ H < 0.91;BG4 = 0.44 ≤ H < 0.86, where H = Holstein fraction;
b_0 = initial body weight; b_1 = linear regression coefficient; b_2 = Quadratic regression coefficient.

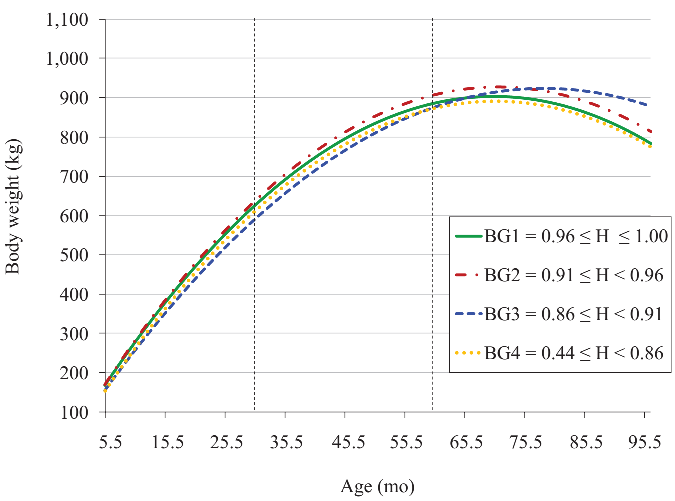

Fig. 3 Growth curves per breed group (BG1–BG4) predicted using the Quadratic model, where H is the Holstein fraction

Table 6 Means and SD of differences between predicted weights with the Quadratic model and actual weights in each growth period by breed group and total

Breed group	Early growth		Late growth		Maturity	
	Mean	SD	Mean	SD	Mean	SD
BG1	-1.97	71.39	-1.39	74.98	17.70	72.89
BG2	-6.28	58.27	-19.55	67.61	-5.71	49.01
BG3	23.78	99.57	27.47	83.45	-14.60	50.44
BG4	15.94	57.38	-3.48	68.13	38.44	60.69
Total	2.68	71.66	-1.64	75.43	7.53	62.98

BG1 = 0.96 ≤ H < 1.00; BG2 = 0.91 ≤ H < 0.96; BG3 = 0.86 ≤ H < 0.91; BG4 = 0.44 ≤ H < 0.86, where H = Holstein fraction.

The weights predicted using the Quadratic model indicated that bulls with an H fraction equal or greater than 96% (BG1) had the fastest rate of early growth and that bulls with an H fraction between 44% and 86% (BG4) had the lowest rate of late growth (Fig. 3). The predicted growth rates of bulls in BG1, BG2 and BG4 followed similar patterns throughout early growth, late growth and maturity. However, although the predicted growth rate of bulls in BG3 was lower than in BG1, BG2 and BG4 during the early and late growth periods, it was higher than these breed groups at maturity. Caution should be exercised when interpreting the predicted weights from the Quadratic model in this population because of the large SD of the differences between predicted and actual weights for all breed groups in all growth phases, particularly for BG3 in the early growth phase.

Meat demand in Thailand per year (181,000 t, equivalent to 1.26 million animals) exceeds the amount of available meat from beef cow-calf operations (0.97 million animals; Osothongs et al., 2016). This unmet demand could be largely covered by feeding excess males from dairy cattle operations (509,524 animals). In a recent meat production study, crossbred steers of unknown H percentage had an average slaughter weight of 576.7 kg (SD =76.0 kg), carcass weight of 312.4 kg (SD = 42.8 kg), dressing percentage of 54.2 % (SD = 2.3 %) and a marbling score of 1.8 (SD = 0.8; Pluemjai et al., 2016). The slaughter weight in that study (576.7 kg) was achieved at age approximately 27 mo for BG1 and BG2, 28 mo for BG4, and 29 mo for BG3, suggesting that the higher the H percentage, the shorter the time to slaughter (assuming similar feeding regimes in feedlots). More intensive fattening regimens could be used to speed up growth and reduce age at slaughter. Growth curves of sires of feedlot steers could be used to help identify bulls whose steer progeny would be expected to have faster growth rates and shorter fattening times. Another use of bull growth information concerns replacement females that have enough growth capability to produce milk under the open-housing, feeding and climatic conditions in Thailand. Predicted bull mature weights for the four bull breed groups (Fig. 3) suggest that daughters of bulls in BG2 and BG3 would tend to be larger than those from BG1 and BG4. However, these are phenotypic rather than genetic predictions. A selection program to select the mature weight of replacement females would require genetic or genomic predictions of all animals in the breeding population (males and females) based on pedigree and weights collected at various ages, as well as genotypes for genomic predictions. Although genotypes are currently collected in the Thai multibreed dairy population, weights are not collected on either males or females. Perhaps a study addressing the economic advantages of genomic selection for meat production with dairy animals would encourage Thai dairy producers to collect weight information.

The Quadratic model provided the best fit to the growth of dairy bulls in the Thai population between ages 5.5 mo and 96 mo. Bull predicted weights increased faster during the early growth phase (age 6 mo to 30 mo), slowed down during the late growth phase (age 30 nth to 60 mo) and tended to decrease during the maturity phase (age 60 mo to 96 mo). Bulls in BG2 ($0.91 \leq H < 0.96$) had the fastest rates of early growth, late growth and at maturity until age approximately 76 mo when it was overtaken by bulls in BG3 ($0.86 \leq H < 0.91$). Bulls in BG3 had the slowest rates during the early and late growth periods and ended up with the fastest rate during the maturity period. Bulls in BG1 and BG4 had intermediate growth rates between BG2 and BG3 during the early and late growth periods and were the slowest in the maturity period. The growth curves of bulls from Thai artificial insemination centers like the DPO would be useful to identify sires expected to produce steers with fast growth rates in the feedlot as well as heifers with younger ages at first calving. Unfortunately, weights from steer and heifer progeny from these bulls were unavailable. Consequently, weights from male and female progeny would need to be collected if genomic selection for growth traits were to be implemented in the Thai dairy multibreed population.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

References

Akaike, H. 1974. A new look at the statistical model identification. IEEE Trans. Automat. Control 19: 716−723.

Berry, D.P., Horan, B., Dillon, P. 2005. Comparison of growth curves of three strains of female dairy cattle. J. Anim. Sci. 80: 151−160.

Brody, S. 1945. Bioenergetics and growth, with special reference to the efficiency complex in domestic animals. Reinhold. New York, NY, USA.

Brown, J.E., Fitzhugh Jr., H.A., Cartwright, T.C. 1976. A comparison of nonlinear models for describing weight-age relationship in cattle. J. Anim. Sci. 42: 810−818.

Burnham, K.P., Anderson, D.R. 1998. Model selection and inference: A practical information-theoretic approach. Springer-Verlag. New York, NY, USA.

Calo, L.L., McDowell, R.E., Van Vleck, L.D., Miller, P.D. 1973. Parameters of growth of Holstein-Friesian bulls. J. Anim. Sci. 37: 417−422.

Cobuci, J.A., Costa, C.N., Neto, J.B., Freitas de, A.F. 2011. Genetic parameters for milk production by using random regression models with different alternatives of fixed regression modelling. R. Bras. Zootec. 40: 3: 557−567.

Dziak, J.J., Coffman, D.L., Lanza, S.T., Li, R. 2012. Sensitivity and specificity of information criteria. https://peerj.com/preprints/1103.pdf, 28 October 2017.

Forni, S., Piles, M., Blasco, A., Varona, L., Oliveira, H.N., Lôbo, R.B., Albuquerque, L.G. 2009. Comparison of different nonlinear functions to describe Nelore cattle growth. J. Anim. Sci. 87: 496−506.

García-Muñiz, J.G., Holmes, C.W., Garrick, D.J. Lopez-Villalobos, N., Wickham, B.W., Wilson, G., Brookes, I.M., Purchas, R.W. 998. Growth curves and productivity of Holstein-Friesian cows bred for heavy or light mature live weight. In: Proceedings of the New Zealand Society of Animal Production. Christchurch, New Zealand, pp, 68−72.

Goldberg, V., Ravagnolo, O. 2015. Description of the growth curve for Angus pasture-fed cows under extensive systems. J. Anim. Sci. 93: 4285−4290.

Gompertz, B. 1825. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Philos. Trans. R. Soc. Lond. 115: 513−585.

Goonewardene, L.A., Berg, R.T., Hardin, R.T. 1981. A growth study of beef cattle. Can. J. Anim. Sci. 61: 1041−1048.

Koonawootrittriron, S., Elzo, M.A., Thongprapi, T. 2009. Genetic trends in a Holstein × other breeds multibreed dairy population in Central Thailand. Livest. Sci. 122: 186−192.

Lee, H., Ghosh, S.K. 2009. Performance of information criteria for spatial models. J. Stat. Comput. Simul. 79: 93−106.

López de Torre, G., Candotti, J.J., Reverter, A., Bellido, M.M., Vasco, P., García, L.J., Brinks, J.S. 1992. Effects of growth curve parameters on cow efficiency. J. Anim. Sci. 70: 2668−2672.

Menchaca, M.A., Jr. Chase, C.C., Olson, T.A., Hammond, A.C. 1996. Evaluation of growth curves of Brahman cattle of various farme sizes. J. Anim. Sci. 74: 2140−2151.

Nelder, J.A. 1961. The fitting of a generalization of the Logistic curve. Biom. 17: 89−110.

Osothongs, M., Khemsawat, J., Sarakul, M., Jattawa, D., Suwanasopee, T., Koonawootrittriron, S. 2016. Current situation of beef industry in Thailand. In: Proceedings of International Symposium: Dairy Cattle Beef Up Beef Industry in Asia: Improving Productivity and Environmental Sustainability. Bangkok, Thailand, pp. 5−8.

Perotto, D., Cue, R.I., Lee, A.J. 1992. Comparison of nonlinear functions for describing the growth curve of three genotypes of dairy cattle. Can. J. Anim. Sci. 72: 773−782.

Pluemjai, C., Koonawootrittriron, S., Suwanasopee, T., Elzo, M.A., Khemsawat, J., Jattawa, D. 2016. A comparative study of carcass yields and quality between fattening Charolais crossbred and Holstein crossbred steers. In: Proceedings of the 5th National Animal Science Conference of Thailand. Khon Kaen, Thailand, pp. 309−316.

Richards, F.J. 1959. A flexible growth function for empirical use. J. Exp. Bot. 10: 290−300.

SAS. 2011. SAS® 9.3 System Options: Reference, 2nd Ed. SAS Institute Inc. Cary, NC, USA.

Schwarz, G. 1978. Estimating the dimension of a model. Ann. Statist. 6: 461−464.

Thai Meteorological Department. 2015. Weather Report for 2004 to 2015. Ministry of Information and Communication Technology. Bangkok, Thailand.

Von Bertalanffy, L. 1957. Quantitative laws in metabolism and growth. Q. Rev. Biol. 32: 217−231.