Analysis of growth of broilers with restricting and unrestriciting initial body weight in Gompertz-Laird model in different environments

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Introduction

Growth trajectory measured as body mass or body weight has been described by mathematical functions fitted to growth curves, particularly in poultry (Laird, 1966; Tseng and Becker, 1981; Ricklefs, 1985; Barbato, 1991, 1992; Remignoni, 1993; Mignon-Graesteau et al., 2000; Maruyama et al., 2001; Aggrey, 2002; Reddish and Lilburn, 2004; Norris et al., 2007). Growth curve models provide a set of parameters that are used to describe growth pattern over time, and to estimate the expected weight of animals at a specific age (Tseng and Becker, 1981; Yakupoglu and Ail, 2001b). In addition, the parameters obtained from growth curve functions are highly heritable and have been used in selection studies (Merritt, 1974; Mignon-Graesteau et al., 2000). There is a set of growth curve functions used to determine age-weight relationship of poultry. The functions have different properties and different mathematical limitations. Among these functions, the Laird form (Laird et al., 1965) of the Gompertz model (Gompertz, 1925) has been the model used to analyse chicken data (Tseng and Becker, 1981; Anthony et al., 1991; Barbato, 1991; Mignon-Graesteau et al., 1999; Aggrey, 2002). The original Gompertz model is a function of mature body weight, whereas the Laird form (Laird et al., 1965) of Gompertz model is a function of initial body weight and inflection point (Barbato, 1991). The performance of the Gompertz-Laird model can be improved by some constraints on the initial body weight (Grossman and Bohren, 1982), or by weighting initial body weight by the inverse of the variance (Pasternak and Shaley, 1994). Moreover, initial body weight can be set within two standard deviation of mean initial body weight as suggested by Mignon-Graesteau et al. (1999). The effect of constraining initial body weight on the other model parameters to improve fitting of data is yet to be investigated (Aggrey, 2002).

Therefore, the purposes of the present study were to investigate the effect of constraining initial body weight on the general fitting of Gompertz-Laird model, and to investigate the effect of environmental changes on the parameters of the model.

Materials and methods

Experimental design

From a commercial hatchery of Ross 308 chicks, 200 males and 200 females were obtained. All birds were wing-tagged and weighed at 3 days of age. Two experiments were carried out in an environmentally controlled house capable of ±1°C temperature control. The broilers were brooded and reared on pine wood shavings litter. Lighting was continuous (24 hours), as access to feed and water. Room temperature was 30.0°C the first 7 days, 27.0°C the second 7 days and 24.0°C the third 7 days. During the first 21 days, birds were fed on a crumbled starter diet. Thereafter, chicks were subjected to the experimental treatments. Two experiments were carried out, experiment 1 and experiment 2. In experiment 1, 36 males and 36 females were reared in 36 pens with two birds of the same sex in one pen under a temperature regimen of 21.0°C from 21 to 42 days; another 36 males and 36 females were reared under a temperature regimen of 30.0°C from 21 to 42 days. Birds for the experiments were selected in such way that each pen (0.5x0.5 m) of two birds were weighed and pen weights were adjusted by replacing individual birds to provide pen weights within 1σp of pen weights for all treatments. Experiment 1 consisted of 3 dietary treatments per temperature subclass. Five diet formulations were used in both trials. For Diet 1, 2, and 4 (based on maize and soybean) the nutrient specifications were set to meet or
exceed NRC (1994) requirements. Diet 3 was essentially Diet 2 without supplemental methionine so that the calculated level of methionine in the feed was 3.1 g/kg. Similarly, Diet 5 was essentially Diet 4 without supplemental methionine so that the calculated level of methionine in the feed was 2.9 g/kg. The ingredients used and the calculated nutrient content of the five diet formulations used in this study are shown in Table 1.

The diets given to birds in weekly bases and experimental treatments (Trt1, Trt2, Trt3) are shown in Table 2. Water was supplied from 2000 mL plastic water bottles fitted with nipples at the base. Each pen was equipped with one hanging feeder and an individual bottle. Feed and water were consumed ad libitum. Incandescent lights were used to provide the birds with 24 hours of light per day. Body weights of each bird were measured at 3 and 7, 14, 21, 28, 35, and 42 days of age.

Experiment 2 was a duplicate of experiment 1, except that birds’ body weight was measured at 49 days of age as well.

Preliminary analyses showed that there was no significant difference in parameter estimates for comparing experiments 1 and experiment 2. Therefore, data obtained from the two experiments were combined and used for growth curve parameters estimation. Thus, a total of 278 birds (142 males and 136 females) had complete growth data.

### Data analysis

The Laird form of the Gompertz model was fit to the data. The Gompertz-Laird growth curve is described by the following equation:

$$ BW_w = BW_0 e^{\left(\frac{L}{K}\left(1-e^{-Kw}\right)\right)} $$

where $BW_w$ is the weight of birds at week $w$, $BW_0$ is the initial body weight, $L$ is the initial specific growth rate per week, $K$ is the rate of exponential decay of the initial specific growth rate. At the inflection point, the following parameters were derived:

$$ t_i = \frac{1}{K} \ln\left(\frac{L}{K}\right) $$

$$ BW_i = BW_0 e^{\left(\frac{L}{K}\right)} $$

where $t_i$ is the inflection point as week, and $BW_i$ is the asymptotic body weight.

Since consecutive or repeated measurements are usually auto-correlated, the growth models were fitted to individual birds in order to remove possible bias in the statistical inference on the growth parameters. The model was run three times for each individual birds in the following manner; in the 1st run, no constraint was applied on $BW_0$ in the 2nd run, $BW_0$ was constrained as the observed initial body weight, that is, the mean of observed initial body weight of all birds was put in the model as a constant, and finally, in the 3rd run, $BW_0$ was allowed to vary within a ±3σ interval around the mean of observed initial body weight of all birds.

Models were compared on the basis of coefficient of correlation ($R^2$), residual standard deviation, and the coefficient of determination ($R^2$).

### Table 1. The ingredient- and calculated nutrient composition of diets.

| Ingredients                                      | Diet 1  | Diet 2  | Diet 3  | Diet 4  | Diet 5  |
|--------------------------------------------------|---------|---------|---------|---------|---------|
| **0-3 wk (%)**                                   |         |         |         |         |         |
| Calcium                                          | 1.00    | 0.90    | 0.90    | 0.80    | 0.80    |
| Total phosphorus                                 | 0.45    | 0.35    | 0.35    | 0.30    | 0.30    |
| Sodium                                           | 0.20    | 0.15    | 0.15    | 0.12    | 0.12    |
| Methionine                                       | 0.52    | 0.38    | 0.32    | 0.32    | 0.29    |
| Cystine                                          | 0.38    | 0.34    | 0.34    | 0.31    | 0.31    |
| Methionine + Cystine                             | 0.90    | 0.72    | 0.66    | 0.63    | 0.60    |
| Lysine                                           | 1.31    | 1.10    | 1.10    | 0.96    | 0.96    |
| Threonine                                        | 0.90    | 0.78    | 0.78    | 0.70    | 0.70    |
| Tryptophan                                       | 0.27    | 0.23    | 0.23    | 0.20    | 0.20    |
| Arginine                                         | 1.61    | 1.37    | 1.38    | 1.21    | 1.21    |
| Isoleucine                                       | 1.00    | 0.86    | 0.86    | 0.76    | 0.76    |
| Leucine                                          | 1.94    | 1.75    | 1.75    | 1.61    | 1.61    |
| Valine                                           | 1.08    | 0.94    | 0.94    | 0.85    | 0.85    |
| Histidine                                        | 0.64    | 0.56    | 0.56    | 0.51    | 0.51    |
| Energy (kcal ME/kg)                              | 3200    | 3200    | 3200    | 3200    | 3200    |

*The composition of vitamins and minerals in the premix provided the following amounts in 2.5 kilogram: vitamin A, 15,000,000 U; vitamin D2, 2,500,000 U; vitamin E, 40,000 mg; niacin, 40,000 mg; pantothenic acid, 10,000 mg; vitamin B2, 7000 mg; vitamin K3, 5000 mg; vitamin B12, 0.03 mg; choline chloride, 300,000 mg. °Calculations are based on analyzed values for corn and soybean meal. #Based on NRC 1994 values for corn and soybean meal.

### Table 2. Diets given to birds in weekly bases.

|          | 4-6 week | 7th week |
|----------|----------|----------|
| **Experiment 1** Trt1 | Diet 2 with normal water | -         |
| Trt2     | Diet 3 with 0.050% methionine in drinking water | -         |
| Trt3     | Diet 3 with 0.075% methionine in drinking water | -         |
| **Experiment 2** Trt1 | Diet 2 with normal water | Diet 4 with normal water |
| Trt2     | Diet 3 with 0.050% methionine in drinking water | Diet 5 with 0.050% methionine in drinking water |
| Trt3     | Diet 3 with 0.075% methionine in drinking water | Diet 5 with 0.075% methionine in drinking water |

0-3 week: all the birds fed with the Diet 1. Trtii: ith dietary-treatment.
Results and discussion

Overall means and standard errors of body weight (BW) for both sexes in relation to environmental changes are represented in Table 3. In all environments, standard errors increased with age in both sexes. Differences in BWs of males and females were significant at week two and thereafter (P<0.05). Males were heavier than females throughout the experiment regardless of the environmental differences. The effect of treatment became apparent at week 4 and remained evident thereafter. The differences in BWs for both males and females were significant (P<0.05) in Trt2 in comparison to those in Trt1 and Trt3. Males and females in Trt1 and Trt3 were heavier than those in Trt2 throughout the experiment. The effect of temperature first appeared at week 5, and stayed significant thereafter. Males and females reared in 21°C were heavier (P<0.05) than those in 30°C. There was no significant interaction between the environmental conditions, and only the main environmental conditions were effective on BW.

In accordance to the choice made about the form of Gompertz-Laird model used (i.e. whether the unrestricted form or one of the restricted ones), differences between the goodness of fit criteria were tested by using t-test procedures. The estimates of the comparison criteria and standard errors in relation to the environmental condition are shown in Table 4.

R² values were decreased significantly (P<0.05) when the restriction applied on BW₀ became more rigid. For example, when the BW₀ was not allowed to vary, that is, when BW₀ was set to the mean of the observed initial body weights, R² values varied from 0.9971 to 0.9974, however, when BW₀ was allowed to vary in an ±3σ interval around the mean of the observed initial body weight, R² values varied from 0.9980 to 0.9983. Moreover, when BW₀ was not restricted, R² values varied from 0.9997 to 0.9998, and were higher than those obtained from each of the restricted form of the model (P<0.05). In agreement with these findings, high R² values were also reported in a study on growth using unrestricted Gompertz model in broilers (Yukagolu and Atli, 2001b) and in Venda and Naked Neck chickens (Norris et al., 2007).

Table 3. Means, standard errors in grams, and number of observations for body weight (BW) at different ages in relation to environments for male and female broilers.

| Te  | Age wk | 1 | 1 | 1 | 1 |
|-----|--------|---|---|---|---|
|     | 1 | 21°C | 2 | 3 | 1 | 30°C |
|     | 4 | 21°C | 2 | 3 | 1 | 30°C |
| M   | 0  | 24  | 57.0±0.98 | 22  | 56.0±1.02 | 25  | 55.8±0.85 | 24  | 56.3±1.00 | 21  | 53.7±0.97 | 26  | 54.4±0.95 |
|     | 1  | 24  | 139.3±4.01 | 22  | 139.9±3.62 | 25  | 139.4±3.14 | 24  | 143.9±3.99 | 21  | 137.6±4.17 | 26  | 136.7±3.34 |
|     | 2  | 24  | 384.0±9.73 | 22  | 386.9±9.28 | 25  | 386.6±8.37 | 24  | 393.8±8.40 | 21  | 385.2±8.72 | 26  | 379.5±8.44 |
|     | 3  | 24  | 732.2±13.90 | 22  | 733.8±14.85 | 25  | 740.1±13.36 | 24  | 770.2±14.14 | 21  | 724.3±17.07 | 26  | 718.9±15.08 |
|     | 4  | 24  | 1272.9±22.92 | 22  | 1248.5±28.49 | 25  | 1268.4±24.52 | 24  | 1323.6±24.27 | 21  | 1204.4±25.71 | 26  | 1250.6±25.64 |
|     | 5  | 24  | 1891.3±36.82 | 22  | 1861.6±41.83 | 25  | 1913.4±33.04 | 24  | 1960.1±35.32 | 21  | 1714.2±34.13 | 26  | 1830.7±32.77 |
|     | 6  | 24  | 2538.5±47.45 | 22  | 2496.4±53.68 | 25  | 2563.6±44.26 | 24  | 2485.0±44.29 | 21  | 2232.1±39.09 | 26  | 2441.1±39.92 |
|     | 7  | 12  | 3300.6±92.16 | 11  | 3226.3±77.54 | 13  | 3221.2±63.40 | 12  | 3116.6±63.32 | 9   | 2751.9±58.10 | 14  | 2953.1±60.46 |
| F   | 0  | 22  | 57.5±0.93 | 23  | 56.2±0.77 | 20  | 56.3±0.96 | 23  | 54.7±1.05 | 27  | 55.8±0.96 | 21  | 56.5±0.94 |
|     | 1  | 22  | 137.4±2.84 | 23  | 140.9±2.87 | 20  | 139.2±3.08 | 23  | 132.6±3.13 | 27  | 137.5±3.35 | 21  | 144.1±3.77 |
|     | 2  | 22  | 372.4±6.41 | 23  | 373.6±7.42 | 20  | 365.8±8.02 | 23  | 362.2±6.44 | 27  | 370.0±5.90 | 21  | 376.4±5.70 |
|     | 3  | 22  | 655.8±8.99 | 23  | 682.9±12.48 | 20  | 674.2±13.08 | 23  | 680.2±10.07 | 27  | 681.6±12.84 | 21  | 685.2±12.60 |
|     | 4  | 22  | 1150.3±18.53 | 23  | 1107.2±17.49 | 20  | 1142.8±25.36 | 23  | 1133.3±16.76 | 27  | 1122.8±20.38 | 21  | 1145.9±21.58 |
|     | 5  | 22  | 1683.4±27.92 | 23  | 1591.8±38.64 | 20  | 1689.4±34.18 | 23  | 1628.8±22.87 | 27  | 1594.0±30.36 | 21  | 1643.3±26.33 |
|     | 6  | 22  | 2178.1±47.21 | 23  | 2101.5±46.05 | 20  | 2229.4±42.10 | 23  | 2136.4±28.59 | 27  | 2067.9±38.85 | 21  | 2130.9±32.19 |
|     | 7  | 10  | 2804.9±46.78 | 11  | 2738.1±48.40 | 8   | 2816.9±67.72 | 11  | 2599.8±29.04 | 15  | 2563.9±35.39 | 9   | 2668.8±49.17 |

Te: temperature. Trt 1: Diet 1 (0-3 wk) + Diet 2 with normal water (4-6 wk) for the experiment 1. Trt 1: Diet 1 (0-3 wk) + Diet 2 with normal water (4-6 wk) + Diet 4 (wk 7) for the experiment 2. Trt 2: Diet 1 (0-3 wk) + Diet 3 with 0.050% methionine in drinking water (4-6 wk) for the experiment 1. Trt 2: Diet 1 (0-3 wk) + Diet 3 with 0.050% methionine in drinking water (4-6 wk) + Diet 5 with 0.050% methionine in drinking water (wk 7) for the experiment 2. Trt 3: Diet 1 (0-3 wk) + Diet 3 with 0.075% methionine in drinking water (4-6 wk) for the experiment 1. Trt 3: Diet 1 (0-3 wk) + Diet 3 with 0.075% methionine in drinking water (4-6 wk) + Diet 5 with 0.075% methionine in drinking water (wk 7) for the experiment 2. M: males, F: females.
Restriction applied on BW0 forced BW0 to take larger values than the model could produce, and since BW0 is a function of BWa, it caused BWa become larger.

Previous studies have suggested ways of improving the fitting of the data. Thus, some restrictions could be put on the initial body weight (Grossman and Bohren, 1982). The observed initial body weight could be used as a constant in the model (Barbato, 1990) or BW0 could be weighted by the inverse of the variance (Pasternak and Shalev, 1994). In addition, Mignon-Grasteau et al. (1999) constrained BW0 to stay within two standard deviations of mean of BW0, and reported a correlation of 0.98 between the observed and the predicted initial body weights. In the present study, we compared the original Gompertz-Laird model with restricted Gompertz-Laird models in which BW0 was restricted in two different ways. Analyses showed that the any restriction on BW0 alone in the Gompertz-Laird model forced the other model parameters to take the values out of parameter space. For example, in cases when BW0 was restricted, asymptotic body weight (BWa) (Table 4) derived by using the estimates of BW0, L, and K, has taken very large values, ranging from 10.1 kg to 73.1 kg. The same situation was observed also for the parameter ti. Consequently, this caused a decrease of the estimation power of the model, which can be seen by examining the RSD, R2, and the correlation (r) between the observed and the estimated growth curves (Table 4). The values of r obtained from the unrestricted Gompertz-Laird model were different and significantly larger (P<0.05) than the r values obtained from the restricted forms of the model.

The estimates of BW0 obtained from the restricted forms of Gompertz-Laird models were not reported here because the estimates were identical and the smallest possible value for all individuals. For example, when the BW0 was restricted to be the mean of the observed initial body weights, naturally all the individuals had the same estimate of BW0. Similarly, when the BW0 was allowed to vary within an interval of ±3σp around the mean of the observed initial body weights, all the individuals had the lowest possible estimate of BW0 and that was the lowest bound of the interval. Without any restriction on BW0, the model significantly (P<0.01) underestimated the observed BW0 in every level of each environmental condition (Table 5). However, considering the other goodness of fit criteria, the unrestricted Gompertz-Laird model performed well, that is, the highest R2, the highest correlation (r) between the observed and the estimated

Table 4. Coefficients of determination (R2), residual standard deviation (RSD), correlation between observed and the predicted growth curves (r), and asymptotic body weight (BWa) values of Gompertz-Laird model restricted in three different ways.

| No. | Restriction on BW0 | Observed | ±3σp of Obs |
|-----|--------------------|----------|-------------|
| R-Square | Temp | 21°C | 0.9897±0.0001* | 0.9975±0.0001 | 0.9883±0.0001 |
| | 30°C | 0.9990±0.0000 | 0.9971±0.0001 | 0.9980±0.0001 |
| | Trt | 1 | 0.9997±0.0000 | 0.9971±0.0002 | 0.9980±0.0001 |
| | | 2 | 0.9997±0.0000 | 0.9974±0.0001 | 0.9983±0.0001 |
| | | 3 | 0.9997±0.0014 | 0.9972±0.0001 | 0.9982±0.0001 |
| | Sex | M | 0.9997±0.0000 | 0.9973±0.0001 | 0.9982±0.0001 |
| | | F | 0.9998±0.0000 | 0.9972±0.0001 | 0.9982±0.0001 |
| RSD | Temp | 21°C | 20.46±0.872 | 70.54±1.224 | 56.79±1.156 |
| | | 30°C | 18.58±0.866 | 74.22±1.416 | 60.58±1.324 |
| | Trt | 1 | 19.07±0.973 | 75.60±1.635 | 61.66±1.556 |
| | | 2 | 19.28±0.975 | 67.79±1.495 | 54.59±1.359 |
| | | 3 | 20.12±1.243 | 73.89±1.673 | 59.94±1.506 |
| | Sex | M | 21.83±0.993b | 75.42±1.380 | 61.52±1.311 |
| | | F | 17.04±0.656b | 69.30±1.231 | 55.81±1.142 |
| r | Temp | 21°C | 0.9997±0.0001 | 0.9982±0.0001 | 0.9987±0.0001 |
| | | 30°C | 0.9997±0.0000 | 0.9997±0.0001 | 0.9995±0.0001 |
| | Trt | 1 | 0.9997±0.0000 | 0.9997±0.0001 | 0.9995±0.0001 |
| | | 2 | 0.9997±0.0000 | 0.9997±0.0001 | 0.9995±0.0001 |
| | | 3 | 0.9997±0.0001 | 0.9980±0.0001 | 0.9986±0.0001 |
| | Sex | M | 0.9997±0.0000 | 0.9981±0.0001 | 0.9986±0.0001 |
| | | F | 0.9997±0.0000 | 0.9989±0.0001 | 0.9986±0.0001 |
| BWa | Temp | 21°C | 6344±159a | 5849±32599 | 15720±1133 |
| | | 30°C | 5027±88b | 4853±32570 | 11347±948 |
| | Trt | 1 | 5585±206a | 20489±32001 | 11916±823 |
| | | 2 | 5838±156a | 73092±50242 | 14781±1559 |
| | | 3 | 6350±153a | 5849±32509 | 15720±1133 |
| | Sex | M | 4963±89b | 19002±1799 | 12191±670 |
| | | F | 17.04±0.656b | 69.30±1.231 | 55.81±1.142 |

*Numbers in each row (for R2, RSD, and r) are significantly different from each other (P<0.05). BW0: initial (hatching) body weight in grams, No: no restriction applied on BW0, Observed: BW0 restricted in three different ways.
The effect of temperature on all growth parameters was significant (P<0.05) (Table 5). The estimates of BW₀ and ti were larger for broilers subjected to 21°C than that for broilers subjected to 30°C. Broilers in 21°C reached the maximum growth rate 4.2 days (i.e. 0.6 w) later than those in 30°C. In high temperature, initial growth rate (L) was high, thus, birds grew fast in the first period of growth trajectory. However, the rate of exponential decay of the initial specific growth rate (K) was also high, thus, the speed of growth of individual birds slowed down in the second period. Consequently, birds in 30°C reached the age at maximum growth earlier than those subjected to 21°C (Table 5) and had smaller mature body weight than individuals subjected to 30°C (Table 4). In the latter group (21°C), the rate of exponential decay of the initial specific growth rate (K) was slow which prolonged the time needed to reach the age at maximum growth (ti) (Table 5). It is generally expected, when the Gompertz-Laird model is fitted, that individuals with higher initial growth rate would reach the age of maximum growth later, consequently, show a lower exponential decay than individuals with lower initial growth rate (Aggrey, 2002). However, the results in the present study revealed that this general expectation does not hold when there is some fluctuation in the environmental conditions. For example, the individual birds in 21°C in this experiment had lower L than those in 30°C, thus, they reached the age of maximum growth later (Table 5). Moreover, regardless of the level of treatment (Trt1, 2, or 3), individuals with different L values reached the age of maximum growth at the same time (Table 5). The results indicate that the exponential decay, K, is the factor affecting the time to reach the age of the maximum growth.
Conclusions

In conclusion, the Gompertz-Laird model without any restriction on initial body weight (BW0) is appropriate for describing the age-liveweight relationship in broilers. The results showed evidence that restricting BW0 results in having very high estimates of the other model parameters. The initial specific growth rate (L), the rate of exponential decay (K) of the initial specific growth rate, and the relationship between L and K vary as the environmental conditions change. The model parameters of BW0, L, and K were also affected by different feeding regimes. Based on the results in this study, it will be necessary to take into account environmental factors in future studies on growth of broilers.

References

Aggrey, S.E., 2002. Comparison of three nonlinear and spline regression models for describing chicken growth curves. Poultry Sci. 81:1782-1788.

Anthony, N.B., Emmerson, D.A., Nestor, K.E., Bacon, W.L., 1991. Comparison of growth curves of weight selected populations of Turkey, Quails, and Chickens. Poultry Sci. 70:13-19.

Barbato, G.F., 1990. Selection for exponential growth rate at different ages: Short term responses. Poultry Sci. 69(Suppl.1): 14 (abstr.).

Barbato, G.F., 1991. Genetic architecture of growth curve parameters in chickens. Theor. Appl. Genet. 83:24-32.

Barbato, G.F., 1992. Genetic architecture of carcass composition in chickens. Poultry Sci. 71:789-798.

Gompertz, B., 1925. On the nature of the function expressive of the law of human mortality, and on a new method of determining the value of life contingencies. Philos. T. Roy. Soc. A 115:513-585.

Gous, R.M., Moran, Jr.E.T., Stilborn, H.R., Bradford, G.D., Emmans, G.C., 1999. Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. Poultry Sci. 78:812-821.

Grossman, M., Bohren, B.B., 1982. Comparison of proposed growth curve functions in chickens. Growth 46:259-274.

Hancock, C.E., Bradford, G.D., Emmans, G.C., Gous, R.M., 1995. The evaluation of the growth parameters of six strains of commercial broiler chickens. Brit. Poultry Sci. 36:247-264.

Knitezova, H., Hyanek, J., Knize, B., Roubicek, J., 1991. Analysis of growth curves in fowl. I. Chickens. Brit. Poultry Sci. 32:1027-1038.

Laird, A.K., 1966. Postnatal growth of birds and mammals. Growth 30:349-363.

Laird, A.K., Tyler, S.A., Barton, A.D., 1965. Dynamics of normal growth. Growth 29:233-248.

Maruyama, K., Vinyard, B., Akbar, M.K., Shafer, D.J., Turk, C.M., 2001. Growth curve analyses in selected duck lines. Brit. Poultry Sci. 42:574-582.

Merrit, E.S., 1974. Selection for growth rate of broilers with a minimum increase in adult size. pp 951-958 in Proc. 1st World Congr. Genet. Appl. to Livest., Madrid, Spain.

Mignon-Grasteau, S., Beaumont, C., Le Bihan-Duval, E., Poivey, J.F., de Rochambeau, H., Richard, F.H., 1999. Genetic parameters of growth curve parameters in male and female chickens. Brit. Poultry Sci. 40:44-51.

Mignon-Grasteau, S., Piles, M., Varona, L., de Rochambeau, H., Poivey, J. P., Blasco, A., Beaumont, C., 2000. Genetic analysis of growth curve parameters for male and female chickens resulting from selection on shape of growth curve. J. Anim. Sci. 78:2515-2524.

National Research Council, 1994. Nutrient Requirements of Poultry. 9th rev. ed. National Academy Press, Washington, DC, USA.

Norris, D., Ngambi, J.W., Benyi, K., Makgab-ilea, M.L., Shimelis, H.A., Nesanvuni, E. A., 2007. Analysis of growth curves of indigenouse male Venda and Naked Neck chic-kens. S. A. J. Anim. Sci. 37:21-26.

Pasternak, H., Shalev, B.A., 1994. The effect of a feature of regression disturbance on the efficiency of fitting growth curves. Growth Develop. Aging 58:33-39.

Reddish, J.M., Liburn, M.S., 2004. A comparison of growth and development patterns in diverse genotypes of broilers. 2. Pullet growth. Poultry Sci. 83:1072-1076.

Remignon, H., 1993. Contribution a l'etude histologique et biochimique des muscles dans deux lignees de poulets a croissance lente ou rapide. Degree Diss., University of Clermont Ferrand, France.

Ricklefs, R.E., 1985. Modification of growth and development of muscles of poultry. Poultry Sci. 64:1563-1576.

Tzeng, R.Y., Becker, W.A., 1981. Growth pattern of body and abdominal fat weight in male broiler chickens. Poultry Sci. 60:1101-1106.

Yakupoglu, C., Attil, H., 2001a. Comparison of growth curve models on broilers I: Parameter estimation. J. Bioscience 1:680-681.

Yakupoglu, C., Attil, H., 2001b. Comparison of growth curve models on broilers II: Comparison of models. J. Bioscience 1:682-684.