Growth Patterns and Developmental Changes of Backfat Thickness in Okinawa Agu Gilts

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(Received : March 15, 2021, Accepted : June 14, 2021)

Abstract: This study clarified the growth patterns and developmental changes of the backfat thickness (BF) of Okinawa Agu gilts regarding their management. Five nonlinear growth models (Logistic, Gompertz, von Bertalanffy, Richards, and Janoschek) were used to describe growth patterns. Weekly, body weight (BW) data from birth to 34 weeks of age were collected. BF at the P2 position from 4 to 34 weeks of age was recorded every 4–5 weeks. Among 23 gilts pigs, 14 were Agu pigs, and nine were Landrace pigs. Animals were allowed fed ad libitum to 16 weeks of age and then reared under restricted feeding (1.3 kg/day for Agu gilts : 2.5 kg/day for Landrace gilts) to 34 weeks of age. Comparison among the five models revealed that the Richards model was the best fit for the growth data based on adjusted R-square (AdjR²) and Akaike’s information criterion (AIC) for both breeds. The Agu gilts showed smaller mature BW, early maturing rate, and earlier weeks of age at the inflection point than Landrace gilts. BF development in Agu gilts was rapid during 4–16 weeks of age under ad libitum feeding but was suppressed after 16 weeks of age under restricted feeding. The breed differences of BF were observed from 8 weeks of age, and Agu gilts had thicker BF than Landrace gilts.

Key words: Okinawa Agu pigs, growth curve, gilts, body weight, backfat thickness

Introduction

Okinawa Agu pigs are only raised in Okinawa Prefecture, and there were approximately 1000 animals in 2020. Their fecundity is characterized by small litter sizes with total number born, number born alive, and number weaned to be 4.7, 4.1, and 3.3, respectively (Touma and Oikawa, 2017). Agu gilts express estrus from around 6 months of age and start breeding after 8 months. Agu pigs are managed according to a specific feeding management regimen (Okinawa Agu Brand Pork Promotion Council, 2008), due to their smaller and slower growth than modern breeds. However, our knowledge of gilt development in Agu pigs is still insufficient and needs to be further accumulated.

The growth rate of replacement gilts influences subsequent reproductive performance and longevity; thus, gilts are moderately developed to avoid overweight since the excessive fat accumulation during the developmental period can cause problems, such as inhibition of reproductive tract development and locomotion difficulties (NARO, 2013). In our previous study, five nonlinear growth models (Logistic, Gompertz, von Bertalanffy, Richards, and Janoschek) were used to...
describe the growth pattern of Agu boars, this revealed that the Richards model provides the best fit (Touma and Oyadomari, 2021). However, growth curves in Agu gilts remain unclear.

Furthermore, BF at the P2 position correlates well with the total body fat (Mullan and Williams, 1990) and is used as a good indicator of body condition of gilts and sows (Maes et al., 2004; Houde et al., 2010; Roongsitthichai and Tummaruk, 2014). There is no information available regarding BF in Agu gilts development. Herein, we investigated and compared the growth pattern and the developmental changes of Agu and Landrace gilts.

**Material and Methods**

Experimental procedures for animal care and use were conducted at the Okinawa Prefectural Livestock and Grassland Research Center in Japan, according to the guidelines for proper conduct of animal experiments of the Science Council of Japan.

**Animals and Management**

Among 23 animals, 14 were Agu purebred, whereas nine were Landrace pigs; they were born in 2016 between May and September. Agu gilts were bred from six sows; and three sows for the Landrace, respectively. The Landrace source is the Okinawa Island, a line selected for higher daily weight gain, lower backfat thickness, larger loin eye muscle area, and larger total litter size of over seven generations at the Okinawa Prefectural Livestock Breeding Center.

Agu gilts were cared for following the manual for feeding and managing Okinawa Agu pigs (Okinawa Agu Brand Pork Promotion Council, 2008), and Landrace gilts were managed according to our conventional regimen. Pigs were weighed at birth and 1 ml of iron (with 200 mg of dextran iron) was administered intramuscularly at 2 days after birth. All female piglets were used as test pigs, two to three pigs per litter for Agu, and three pigs per litter for Landrace. The piglets were weaned at 28 days of age. Pigs from the same litter were reared together from birth to 16 weeks. From birth to seven weeks of age, the pigs were housed in farrowing pens, and from 7 to 16 weeks of age, they were group-housed, with three to five pigs per pigpen of 2.7×2.7 m. After 16 weeks, they were housed individually in single pens of 2.7×1.2 m. The pigs were fed five commercial diets during five different time intervals: three days to 4 weeks (first stage), 4–6 weeks (middle stage), 6–10 weeks (late stage), 10–16 weeks, and 16–34 weeks. The ingredients and chemical composition of the experimental diets are presented in Table 1. Replacement gilts are reared under restricted feeding after they reach a weight of over 60 kg for modern breeds and 40 kg for Agu pigs, since excessive fat accumulation during the developmental period can cause problems such as difficulty in locomotion (NARO, 2013; Okinawa Agu Brand Pork Promotion Council, 2008). In this study, until 16 weeks of age, the pigs were fed ad libitum, after that, they were reared under restricted feeding conditions of 1.3 kg/day for Agu and 2.5 kg/day for Landrace, respectively. The pigs were provided with free water access throughout and fed manually. According to the Japanese feeding standard for swine, replacement gilts of modern breeds need to be fed 2.19–2.44 kg/day food depending on their BW (60–130 kg) (NARO, 2013), but since the Landrace used in this study is a lean type and does not gain fat easily, a fixed amount of 2.5 kg/day food was fed, which is more than the recommended amount. Regarding Agu gilts, there is no weight-based feeding program for restricted feeding, and we empirically fixed the feeding amount at 1.3 kg/day to avoid overweight.

**BW and BF measurement**

BW was collected weekly from birth to 34 weeks of age. BF was measured at 4–5 week intervals from 4 to 34 weeks of age and was taken by the same measurer throughout the study. The 4-week-old pigs were lifted and held and >8-week-old pigs were held using a snout rope. BF measurements were performed at the P2 position on the right side of the animal using an ultrasonic lean meter (Anyscan BF; SongKang GLC Co., Ltd.). BF layer grew from the first to the third
layer, and the value of the largest layer was used.

One of the Landrace gilt had a leg injury at 27 weeks of age; therefore, no data was gathered from the pig after the injury.

**Growth Curve Models**

Before fitting to the growth curves, the sow effects were removed from BW data, as described by our previous study (Touma and Oyadomari, 2021). The corrected BW for each individual was fitted to the growth curve models. The least square means, SD, and CV of the corrected BW are shown in Table 2. The growth curve models used in this study were Logistic (Wellock et al., 2004), Gompertz (Gompertz, 1825), von Bertalanffy (von Bertalanffy, 1957), Richards (Fitzhugh, 1976), and Janoschek models (Wellock et al., 2004). The equations and their derived parameters are presented in Table 3. $Y_t$ represents the body weight (kg) at age $t$ (weeks), $A$ is the weight at maturity (kg), $B$ is an integration constant, $k$ is the maturation rate, and $M$ is the inflection parameter, which is specific to the Richards and Janoschek models. The estimation of the nonlinear growth curves was performed using the nls function of R 3.4.2 (RCORE TEAM, 2017). The goodness of fit of the five growth models was compared using the adjusted coefficient of determination (AdjR$^2$) and Akaike’s information criterion (AIC). A model which has higher AdjR$^2$ and smaller AIC indicates a better fit when comparing models.

**Statistical Analysis**

The final data set consisted of 806 and 184 records of BW and BF, respectively. Data were analyzed using the general linear model procedure in the JMP software (SAS Institute Inc.). The differences in the growth curve parameters between breeds were analyzed using a one-way analysis of variance as follows:

$$Y_{ij} = \mu + G_i + e_{ij}.$$

Where: $Y_{ij}$ is the growth curve parameter of breed $i$; $\mu$ is the overall mean; $G_i$ fixed effect of $i$th breed and $e_{ij}$ is the random error.

BF at the P2 position was analyzed using the model

$$Y_{ijkn} = \mu + G_i + m_{ij} + W_k + (GW)_{ik} + d_{ijn} + e_{ijkn},$$

Where: $Y_{ijkn}$ is the BF at week $k$ of the $n$th gilt born to sow $j$ of breed $i$; $\mu$ is the overall mean; $G_i$ fixed effect of $i$th breed; $m_{ij}$ is random effect $j$th sow within $i$th breed; $W_k$ fixed effect of $k$th week; $(GW)_{ik}$ fixed interaction of breed $i$ and week $k$; $d_{ijn}$ is random effect $nth$ gilt within breed $i$ and sow $j$; and $e_{ijkn}$ is the random error.

Significant differences in mean values were confirmed using Tukey-Kramer comparison tests.
(P<0.05). Additionally, the analysis results for BF indicated an interaction between breed and weeks of age (P<0.001). Therefore, the difference in the least square means between breeds was compared for each week of age (4, 8, 12, 16, 21, 25, 29, and 34 weeks).

Table 2. Descriptive statistics of least square means and standard deviations of the body weight of Agu and Landrace gilts

| Week | n | BW | SD  | CV  | n | BW | SD  | CV  |
|------|---|----|-----|-----|---|----|-----|-----|
| 0    | 14| 1.1| 0.24| 0.22| 9 | 1.6| 0.20| 0.12|
| 1    | 14| 2.0| 0.37| 0.19| 9 | 4.1| 0.56| 0.14|
| 2    | 14| 3.4| 0.58| 0.17| 9 | 6.2| 0.90| 0.14|
| 3    | 14| 4.7| 0.77| 0.16| 9 | 9.3| 1.34| 0.14|
| 4    | 14| 6.6| 0.92| 0.14| 9 | 12.3| 1.23| 0.10|
| 5    | 14| 9.7| 1.63| 0.17| 9 | 15.2| 1.51| 0.10|
| 6    | 14| 12.2| 1.72| 0.14| 9 | 18.9| 1.49| 0.08|
| 7    | 14| 15.3| 1.93| 0.13| 9 | 22.7| 1.40| 0.06|
| 8    | 14| 18.0| 1.96| 0.11| 9 | 27.9| 1.79| 0.06|
| 9    | 14| 21.4| 2.12| 0.10| 9 | 30.3| 2.10| 0.07|
| 10   | 14| 24.6| 2.29| 0.09| 9 | 34.9| 1.35| 0.04|
| 11   | 14| 27.9| 3.18| 0.11| 9 | 40.2| 1.91| 0.05|
| 12   | 14| 32.2| 3.19| 0.10| 9 | 44.7| 2.04| 0.05|
| 13   | 14| 35.9| 3.16| 0.09| 9 | 50.5| 1.79| 0.04|
| 14   | 14| 39.5| 2.75| 0.07| 9 | 56.8| 2.26| 0.04|
| 15   | 14| 41.9| 2.42| 0.06| 9 | 60.8| 1.63| 0.03|
| 16   | 14| 45.2| 3.32| 0.07| 9 | 65.7| 1.31| 0.02|
| 17   | 14| 48.7| 3.67| 0.08| 9 | 71.4| 1.23| 0.02|
| 18   | 14| 52.2| 3.64| 0.07| 9 | 77.6| 1.63| 0.02|
| 19   | 14| 55.4| 3.69| 0.07| 9 | 83.2| 2.33| 0.03|
| 20   | 14| 56.5| 3.54| 0.06| 9 | 90.5| 1.84| 0.02|
| 21   | 14| 58.4| 3.59| 0.06| 9 | 94.9| 3.45| 0.04|
| 22   | 14| 59.7| 3.59| 0.06| 9 | 100.7| 2.98| 0.03|
| 23   | 14| 61.4| 3.63| 0.06| 9 | 103.2| 2.59| 0.03|
| 24   | 14| 63.3| 3.85| 0.06| 9 | 105.7| 2.85| 0.03|
| 25   | 14| 65.8| 3.83| 0.06| 9 | 110.4| 3.36| 0.03|
| 26   | 14| 67.4| 3.67| 0.05| 9 | 112.7| 4.70| 0.04|
| 27   | 14| 69.1| 3.29| 0.05| 9 | 115.7| 5.40| 0.05|
| 28   | 14| 70.8| 3.28| 0.05| 8 | 116.8| 2.45| 0.02|
| 29   | 14| 72.5| 2.98| 0.04| 8 | 120.0| 4.64| 0.04|
| 30   | 14| 73.4| 3.05| 0.04| 8 | 122.7| 4.80| 0.04|
| 31   | 14| 75.4| 3.27| 0.04| 8 | 127.1| 5.00| 0.04|
| 32   | 14| 76.5| 3.02| 0.04| 8 | 131.5| 5.73| 0.04|
| 33   | 14| 77.7| 3.02| 0.04| 8 | 136.8| 5.04| 0.04|
| 34   | 14| 78.8| 3.26| 0.04| 8 | 142.4| 5.43| 0.04|

Results and Discussion

The growth pattern of Agu and Landrace gilts

The five growth curves showed a typical sigmoid shape and generally had the same behavioral pattern (Fig. 1). Agu and Landrace gilts showed a decrease in growth rate from 20 weeks
and 23 weeks, respectively, probably due to the effects of restricted feeding from 17 weeks of age.

The AdjR\(^2\) and AIC of the five models are presented in Table 4. The AdjR\(^2\) ranged from 0.9922 to 0.9987, and the Richards model had the highest value for Agu and Landrace gilts. The Richards model also had the smallest AIC value for both breeds. The Logistic, Gompertz, von Bertalanffy, Richards, and Janoschek models are often used to fit growth curves for pigs (Wellock et al., 2004), cattle (Brown et al., 1976), quail (Kaplan and Gürçan, 2018), and other animals (Hojjati and Ghavi Hossein-Zadeh, 2018). Here, these five models had AdjR\(^2\) values above 0.99, describing Agu and Landrace gilts’ growth reasonably well. The Richards and Janoschek models had four parameters, one more than the other models, and they flexibly represent the inflection point, leading to a better depiction of the growth curve; especially, many studies reported that the Richards model provided the best fit (Kebreab et al., 2007; Köhn et al., 2007; Kaplan and Gürçan, 2018). In this study, the Richards model was the best fit among the five models for Agu and Landrace gilts, based on AdjR\(^2\) and AIC values. Alternatively, the Logistic model provided the worst fit with the lowest AdjR\(^2\) and highest AIC values among the five models, overestimating BW, especially at an early age. The present results were consistent with our previous study, in which we applied Logistic, Gompertz, von Bertalanffy, Richards, and Janoschek models to describe the growth pattern of Agu boars (Touma and Oyadomari, 2021). The Richards model provides a decision-making criterion for producers to evaluate the growth rate of Agu gilts.

Table 5 shows the growth curve parameters and inflection point traits of the Richards model, which is the best-fit model. As expected, the mature weight (A) was significantly higher in Landrace than in Agu gilts (200.1 vs. 89.1 kg; P<0.001). However, the maturation rate (k) tended to be greater in Agu than in Landrace gilts (P=0.051). A greater k value indicates early-maturing breeds.
suggesting that Agu gilts mature at an earlier age than Landrace gilts. Animals have a maximum growth rate at the inflection point (Brody, 1945). Landrace gilts had the higher inflection BW (62.7 vs. 26.7 kg; P<0.001) and maximum growth rate (764.4 vs. 494.1 g; P<0.001) than Agu gilts. In contrast, the inflection point weeks of age was earlier in Agu than in Landrace gilts (10.4 vs. 15.1 weeks; P<0.001). Thus, Agu gilts reached the inflection point at a younger age than the Landrace gilts.

In our previous study (Touma and Oyadomari, 2021), the A and k of Agu boars were estimated to be 90.2 kg and 0.09, respectively, similar to those of gilts, but the inflection point was estimated to be 11.6 weeks, which was 1.2 weeks later than that of gilts, suggesting that gilts reach maximum growth rate earlier than boars. On the other hand, the maximum growth rate of boars was 496.9 g, which was similar to that of gilts.

Developmental changes of BF

The trend of BF development for Agu and Landrace gilts is shown in Fig. 2. BF of Agu gilts increased linearly until 16 weeks when they were fed ad libitum. After switching to restricted feeding, its development tended to decrease to 21 weeks, then it became almost constant. The value of BF was 23.3 mm at 34 weeks of age. During the growth phase, energy intake is prioritized for maintenance and lean accretion, and the remainder is assigned to fat accretion (Patience et al., 2015).

![Graph showing growth curves of Agu and Landrace gilts](image)

**Fig. 1.** Growth curves of Agu and Landrace gilts estimated using the Logistic, Gompertz, von Bertalanffy, Richards and Janoschek models.

| Breed | Agu  | Landrace | SEM  | P-value |
|-------|------|----------|------|---------|
| A     | 89.1 | 201.0    | 16.2 | <0.001  |
| B     | 0.72 | 0.58     | 0.22 | 0.191   |
| k     | 0.09 | 0.07     | 0.004 | 0.051   |
| M     | 4.12 | 4.72     | 2.56 | 0.912   |
| t     | 10.4 | 15.1     | 0.66 | <0.001  |
| W     | 26.8 | 62.7     | 4.35 | <0.001  |
| G     | 494.1| 764.4    | 29.4 | <0.001  |

A, size at maturity (kg); B, integration constant; k, maturation rate; M, inflection parameter; t, Inflection point week of age; W, Inflection point body weight; G, Inflection point daily weight gain. Differing superscript letters within the same row indicate significant differences between Agu and Landrace gilts at P<0.001.
Accordingly, it appears that during ad libitum feeding of high energy intake, extra energy was used for fat accretion; however, during restricted feeding, the allocation to fat accretion was drastically reduced. In particular, BF tended to decrease from 16 to 25 weeks of age, suggesting that fat was broken down and used as an energy source. In Landrace gilts, BF development also slowed down after 21 weeks due to restricted feeding.

Because fat gilts and sows have locomotion difficulties (Bortolozzo et al., 2009) and more stillborn piglets due to increased farrowing difficulties (Oliviero et al., 2010), replacement gilts are generally reared under restricted feeding from about 60 kg (NARO, 2013). In this study, restricted feeding was also applied to Agu gilts from over 40 kg (16 weeks of age) according to the feeding management manual for Agu pigs. Our study confirmed that restricted feeding suppressed the development of BF in Agu and Landrace gilts. However, gilts with too thin backfat had a lower reproduction performance and longevity (Stalder et al., 2005; Roongsittichai and Tummaruk, 2014). Therefore, some BF level is needed, and even in lean meat types with less fat accumulation, more than 13 mm is required at first insemination (NARO, 2013). The Landrace in this study was a line selected for a thinner BF, and its BF value at 34 weeks of age was 15.6 mm, which met this criterion. Alternatively, no data on the relationship between BF and reproductive performance is available for Agu gilts, and the appropriate BF range remains unclear.

Although the experimental period in this study was the gilt development period of up to 34 weeks of age, the goal of gilts development is to build the body reserves needed for the lifetime productivity (Whitney and Masker, 2010). Therefore, to identify the required BF range for Agu gilts, it is necessary to monitor the trends of BF at breeding, gestation, farrowing, and weaning through multiple parities and to examine the relationship between BF and reproductive performance.

Agu had more BF compared with Landrace gilts after 8 weeks of age (P<0.001). Thicker BF of Agu pigs was reported by a previous study (Touma et al., 2017), which compared Agu and LWD fattening pigs. However, no significant difference was found in BF at four weeks of age, indicating that fat...
accumulation in Agu becomes faster than in Landrace gilts after 4 weeks of age. Similar results were reported for Jinhua pigs, a fatty native Chinese pig by Miao et al. (2009), who studied the developmental changes of BF in Jinhua and Landrace pigs at 35, 80, and 125 and found that significant differences occurred from 80 days of age.

In summary, our study demonstrated that the Richards model provides the best fit to describe the growth pattern of Agu gilts among the five growth models. BF development in Agu gilts was rapid when fed ad libitum, but was suppressed after switching to restricted feeding. This study’s findings would help producers judge the growth rate and body condition and provide important insights for developing more appropriate feed management programs of Agu gilts.

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沖縄アグー繁殖育成雌豚の発育および背脂肪厚の発達

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(2021 年 3 月 15 日受付、2021 年 6 月 14 日受理)

要 約 アグー繁殖育成雌豚の飼養管理技術の確立に向けた基礎的知見を得ることを目的に、発育および背脂肪厚の発達について調査を行った。発育は、生時から 34 週齢まで 1 週間間隔で測定された体重記録に Logistic、Gompertz、von Bertalanffy、Richards および Janoschek の 5 種類の発育曲線モデルを当てはめた。背脂肪厚については、P2 部位を 4 週齢から 34 週齢にかけて 4〜5 週間間隔で測定した。アグー雌 14 頭、対照としてランドレース種雌 9 頭を用い 16 週齢までは不断給餌、16 週齢以降はアグー 1.3 kg/日、ランドレース種 2.5 kg/日の制限給餌を行った。発育曲線の適合度を自由度調整済決定係数 (AdjR²) と赤池の情報量基準 (AIC) でみると、両品種とも Richards が最も優れていた。アグーはランドレース種と比べて成熟体重 (A) は小さいものの、成熟速度 (k) は大きい傾向を示し早熟で、発育速度のピークとなる変曲点への到達週齢も早かった。アグーの背脂肪厚は不断給餌を行っていた 16 週齢までは急激に増加し、制限給餌後は発達が抑制された。背脂肪厚の品種間差は 8 週齢から認められ、アグーがランドレース種よりも有意に厚かった。

キーワード：沖縄アグー豚、発育曲線、繁殖育成雌豚、体重、背脂肪厚