









Nonlinear equations to determine the growth curve of immunocastrated pigs

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Abstract – The objective of this work was to compare the performance of the nonlinear Gompertz, logistic, and von Bertalanffy equations, to describe the growth curve of immunocastrated male pigs from birth until reaching 140 kg body weight. Standard error, number of iterations, mean square of the error, and coefficient of determination were compared between the models. The logistic and von Bertalanffy equations do not accurately estimate the initial and slaughter weights. The Gompertz equation shows the highest reliability and is, therefore, the most suitable one to describe the growth curve of immunocastrated pigs from birth until 140 kg body weight is reached.

Index terms: Gompertz, growth rate, logistic equation, von Bertalanffy.

Equações não lineares para determinar a curva de crescimento de suínos imunocastrados

Resumo – O objetivo deste trabalho foi comparar o desempenho das equações não lineares de Gompertz, logística e a de von Bertalanffy, para descrever a curva de crescimento de suínos machos imunocastrados, desde o nascimento até atingirem 140 kg de massa corporal. O erro-padrão, o número de iterações, o quadrado médio do erro e o coeficiente de determinação foram comparados entre os modelos. A equação logística e a de von Bertalanffy não estimam com precisão as massas inicial e de abate. A equação de Gompertz apresenta maior confiabilidade e é, portanto, a mais adequada para descrever a curva de crescimento de suínos imunocastrados, desde o nascimento até a obtenção de 140 kg de massa corporal.

Termos para indexação: Gompertz, taxa de crescimento, equação logística, von Bertalanffy.

Nonlinear equations have been used in animal production to study and interpret biological processes (for instance the animal growth), and to understand the population dynamics in the production environment. Growth curves show an exponential or sigmoidal pattern, and they are modeled by nonlinear equations (Nascimento et al., 2017).

The description of growth curves of animals over time is essential for the development of mathematical models to estimate the growth, as well as to determine nutritional requirements and the ideal moment for slaughter (Carabús et al., 2017; Remus et al., 2020). Growth curves are generated by relating the weights (“Y”) and ages (“t”) of the animals, using nonlinear equations (Fernandes et al., 2019). Equations used to describe animal growth include the Gompertz, logistic, and von Bertalanffy equations (Iglesias et al., 2014). The number of parameters,

ease of measurement, and estimation precision are the criteria used to determine the equation to estimate animal growth (Kyriazakis & Whittemore, 2006).

New technologies such as immunocastration modify the growth rate of animals and, consequently, their growth pattern (Carabús et al., 2017). Immunocastration involves the intramuscular application of the gonadotropin-releasing hormone (GnRH). This analogue is recognized by the organism, which then starts to fight it, as an antigen. Since the analogous compound to GnRH does not have receptors to complete the connection with the hypophysis, it blocks the testosterone production by the animal (Kress et al., 2019). However, there have been no studies indicating the best equation for describing the growth of immunocastrated male pigs (*Sus scrofa domestica* L.).

The objective of this work was to compare the performance of nonlinear Gompertz, logistic, and von Bertalanffy equations, to describe the growth curve of immunocastrated pigs from the birth until reaching 140 kg body weight.

The protocols used were approved by the Animal Ethics Committee of Universidade Federal de Santa Maria (UFSM, protocol number 8688070716). The experiment was divided into three stages: lactation phase, nursery phase, and growing-finishing phase. Sixty male piglets (Agroceres x Danbred) were monitored during the lactation phase, with 1.422 ± 0.600 kg initial mean body weight. In this period, the animals were individually weighed, weekly, until 28 days of age.

In the nursery (from 29 to 69 days of age) and growing-finishing phase (from 70 days of age to the age of slaughter, 174 days), the pigs were housed in five stalls with capacity for 12 animals each. The bays were equipped with the feeding station FIRE (feed intake recording equipment) and two drinking nipples. During this period, the animals were subjected to a diet program of four ad libitum diets, formulated according to the nutritional requirements of the NRC (2012), as follows: initial phase 1 (I1, 6 to 9 kg), 3,400 kcal kg⁻¹ of metabolizable energy (ME), and 1.58% of digestible lysine (DL); initial phase 2 (I2, 9 to 15 kg), 3,375 kcal kg⁻¹ ME, and 1.33% DL; initial phase 3 (I3, 15 to 30 kg), 230 kcal kg⁻¹ ME, and 1.01% DL. During the growth and termination phases, the following diets were administered: growth phase 1 (C1, 24 to 50 kg), 3,250 kcal kg⁻¹ ME, and 1.09% DL; growth phase 2 (C2, 51 to 70 kg), 3,250 kcal kg⁻¹ ME, and 1.01% DL;

termination phase 1 (T1, 71 to 100 kg), 3,250 kcal kg⁻¹ ME, and 0.81% DL; and termination phase 2 (T2, 101 to 140 kg), 3,100 kcal kg⁻¹ ME, and 0.75% DL.

In the growing-finishing phase, the animals were weighed individually in real time by the feeding station FIRE, and they were immunocastrated according to the vaccination protocol of the product manufacturer. The first and second doses of Vivax (200 µg GnRH-Protein mL⁻¹). (Zoetis, São Paulo, SP, Brazil) were subcutaneously applied (2 mL) in animals at 16 and 23 weeks of age, respectively.

The nonlinear Gompertz, logistic, and von Bertalanffy models were fitted to the weight-age data of the pigs via nonlinear regression, using the Minitab statistical program (McKenzie & Goldman, 2010). The growth rate and inflection point in relation to the body weight and age of the animals were calculated according to the equations (Table 1). The mean squared error (MSE), coefficient of determination (R²), standard error (S), number of iterations, and the biological interpretation of the parameters were analyzed for each equation, to determine which one was the most appropriate for estimating the body growth of the pigs.

When comparing the estimates of weight at maturity, or asymptotic weight ("A"), obtained by the different nonlinear equations for body weight (BW) of immunocastrated pigs, the logistic equation (logE) showed a lower-A value (169.0 kg per BW) than the Gompertz equation (gpzE, 255.7 kg per BW) and von Bertalanffy (berE, 398.8 kg per BW) equations (Table 1). It has been previously reported that logE estimates lower weights at maturity, ranging from 99.9 to 149.0 kg per BW, while berE generally estimates high-A values for pigs, ranging from 243.0 to 329.0 kg per BW (Freitas, 2005; Fernandes et al., 2019). However, gpzE frequently estimates more realistic values of A, ranging from 222.7 to 259.5 kg per BW (Freitas, 2005; Casas et al., 2010; Coyne et al., 2015; Luo et al., 2015).

The parameter B in the logistic and von Bertalanffy equations represents the degree of maturity of the animal at birth. High values of B represent low degrees of maturity at birth. According to Freitas (2005), the parameter B has no biological interpretation, but it is important to model the sigmoidal curve from birth ($t=0$) until adulthood ($t \rightarrow \infty$). The parameter K indicates the animal growth rate, and determines the growth rate

up to the asymptotic weight, from the animal's initial weight. Thus, the higher the value of K, the faster the animal will approach its weight at maturity.

Out of the three nonlinear equations evaluated, logE showed the highest value of K (0.027 kg per day). Higher values of K concentrate growth around the inflection point, increase the maximum growth rate, and reduce the weight at maturity estimated by the growth curve. And smaller values of K, as estimated by berE (0.006 kg per day) indicate that growth is more distributed over time, increasing the estimated asymptotic weight. The growth rates estimated by gpzE and berE were similar to those determined by Carabús et al. (2017), who used the Gompertz equation (0.012 kg per day), and Kebreab et al. (2007), who used the von Bertalanffy equation (0.006 kg per day).

When A and K were evaluated, it was possible to observe that the asymptotic weight, and that there was a decrease of the maturity rate. This antagonistic behavior has been reported by other authors (Freitas, 2005; Coyne et al., 2015).

In general, all equations showed a good fit to the data. However, gpzE and berE showed the highest values of R² and the smallest number of iterations, which resulted in more accurate estimates of the

animal BW, as also observed by Luo et al. (2015) and Fernandes et al. (2019).

The evaluation of growth curves for the observed weights and age-predicted weights, based on the parameters estimated by the nonlinear equations. Figure 1, showed that gpzE gave the best estimate of the weights of the animals, in relation to the weights observed during their lives; logE overestimated the

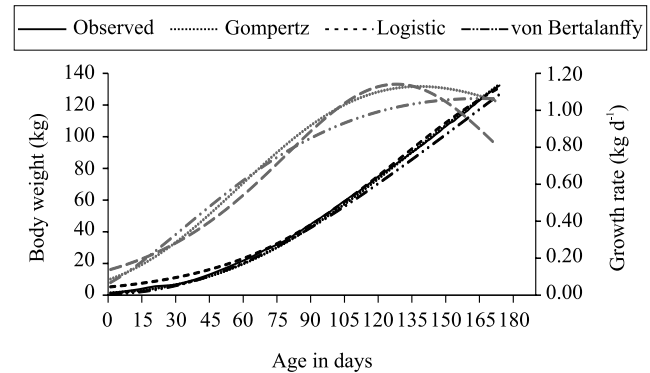


Figure 1. Mean of observed weights, predicted weights by age (black lines), and growth rates (gray lines), estimated by derivatives of Gompertz, logistic, and von Bertalanffy equations of immunocastrated pigs, from birth until 140 kg body weight was reached (age of slaughter, 174 days).

Table 1. Parameterization of the nonlinear equations to estimate the growth curve of immunocastrated male piglets (*Sus scrofa* domesticus) (Agroceres x Danbred) from birth until 140 kg body weight.

Model	Equations	Weight IP	Age IP
Gompertz	$Y = A \cdot \exp(-\exp(-K \cdot (t-C)))$	$= A/e$	$= C$
Logistic	$Y = A / (1 + B \exp(-K \cdot t))$	$= A/2$	$= (\ln(B))/K$
von Bertalanffy	$Y = A \cdot (1 - B \exp(-K \cdot t))^3$	$= (8 \cdot A)/27$	$= \log(e) \cdot (3 \cdot B)/K$
Growth rate of nonlinear equations (first derivative)			
Gompertz	$Y = A \cdot K \cdot \exp(-K \cdot (t-C)) \cdot \exp(-\exp(-K \cdot (t-C)))$		
Logistic	$Y = (A \cdot B \cdot K \cdot \exp(K \cdot t)) / ((B + \exp(K \cdot t))^2)$		
von Bertalanffy	$Y = 3 \cdot A \cdot B \cdot K \cdot \exp(-3 \cdot K \cdot t) \cdot (B - \exp(K \cdot t))^2$		
Parameters	Gompertz	Logistic	von Bertalanffy
A (kg per BW)	255.7	169.0	398.8
B	-	31.747	0.902
K (kg per day)	0.012	0.027	0.006
C (day)	138.4	-	-
Weight IP (kg per BW)	94.09	84.52	118.1
Age IP (days)	138	128	196
Iterations	5	6	5
MSE	68.8944	70.6139	68.9213
S	8.30027	8.40321	8.30189
R ²	0.9994	0.9977	0.9996

IP, inflection point of the sigmoidal curve; e, base of the Neperian logarithm (e, 2.71828); Y, body weight at age t; A, weight at maturity; B, constant integration; C, age at which the maximum growth rate is reached, which is the inflection point of the sigmoidal curve; K, growth rate; MSE, mean squared error; S, standard error; R², determination coefficient.

BW from birth up to 42 days of age. Based on the estimates of the A and B parameters of logE, the birth weight of the animals would be 5.229 kg per BW, a value considered physiologically unfeasible, as the mean birth weight predicted from the individual curve of the animals was 1.422 kg per BW. Luo et al. (2015) also observed that logE overestimated weights in the initial stage (birth to 50 days) of Liangshan pigs: the birth weight estimated by logE of these animals was 4.130 kg per BW, and the real weight was 0.770 kg per BW.

The berE underestimated the birth weight and the weights from 110 to 174 days of age (slaughter). The weights at birth and slaughter estimated by berE were 0.982 kg and 5.522 kg lower than the observed mean birth weight (0.441 vs 1.422 kg per BW) and slaughter weight (126.7 vs 132.3 kg per BW), respectively. Freitas (2005) used berE to describe the growth curve of Large White male pigs from birth to sexual maturity, and found that this equation underestimated the birth weight of these animals by 0.150 kg. However, Luo et al. (2015) found that berE overestimated the slaughter weight of the animals by 0.420 kg. The greater accuracy in the estimation of the slaughter weight observed in the present study may be a consequence of the greater number of weights recorded close to adult age (250 days of age), which increased the accuracy of the estimates of the growth curve (Kyriazakis & Whittemore, 2006).

As berE showed the lowest-K value (0.006 kg per day) of the three equations (Table 1), the age (196 days) and BW (118.1 kg) at the inflection point of the sigmoid curve (IP) were higher than that for gpzE (138 days and 94.09 kg per BW) and logE (128 days and 84.52 kg per BW).

The Gompertz, logistic, and von Bertalanffy equations showed a good fit to the growth data of pigs. However, the logistic equation overestimated the birth weight, and the von Bertalanffy equation underestimated both the birth weight and slaughter weight of the animals. The Gompertz equation accurately estimated the initial and slaughter weights of the pigs, and its parameters (A, K, C) have a biological significance. Therefore, the Gompertz equation shows the highest reliability and is the most suitable equation for describing the growth of immunocastrated pigs from birth until 140 kg body weight is reached.

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