Parameter Estimation of Fat Deposition Models in Beef Steers.

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EXTENDED ABSTRACT

The Davis Growth Model is a dynamic steer growth model encompassing 4 fat deposition models. The Davis Growth Model is currently being used by the phenotypic prediction program of the Cooperative Research Centre (CRC) for Beef Genetic Technologies to predict 12/13th rib fat (mm) in beef cattle.

The concepts of cellular hyperplasia and hypertrophy are integral components of the Davis Growth Model. The net synthesis of total body fat (kg) is calculated from the net energy available after accounting for energy needs for maintenance and protein synthesis. Total body fat (kg) is then partitioned into 4 fat depots (intermuscular, intramuscular, subcutaneous, and visceral) (Figure 1).

The parameters for maintenance, protein synthesis, and the 4 fat depot deposition models (intermuscular, intramuscular, subcutaneous, and visceral fat) were estimated using the parameter estimation routine in acslXtreme (Hunstville, Alabama USA, Xcellon). The first-order fat deposition differential equations are described, the steps taken to parameterize the fat deposition models are outlined, and a sensitivity analysis is performed.

Data comprising 165 mean values of carcass characteristics from various treatments reported in 36 publications from a meta-analysis study of implanted and nonimplanted steers across a range of frame sizes were used. Twenty-one treatments had missing values and 3 did not meet the convergence criteria.

Mean parameter estimates for protein synthesis ($kg^{0.27}$) were 0.0487 ± 0.0001 and 0.0467 ± 0.0001 for implanted (n = 97) and nonimplanted (n = 44) steers, respectively and parameter estimates for maintenance ($Mcal.kg^{-0.75}.day^{-1}$) were 0.1133 ± 0.0014 and 0.1035 ± 0.0026, for implanted (n = 97) and nonimplanted (n = 44) steers, respectively. A 4.1% increase in the protein synthesis parameter was detected between implanted and nonimplanted steers.

Analysis of the fat depot parameters (1/kg deoxyribonucleic acid (DNA)) indicated that the depots are not metabolically different between frame sizes and implant status at the level of aggregation used to simulate fat deposition in beef steers. Therefore, the mean (n = 141) of the 4 fat depot parameter coefficients (1/kg DNA) were 0.1596 ± 0.0061, 0.3447 ± 0.0049, 0.2715 ± 0.0061, and 0.2242 ± 0.0063 for intermuscular, intramuscular, subcutaneous, and visceral fat, respectively.

A sensitivity analysis, with individual incremental changes of ± 10% to each fat depot parameter of 1) the sums of squares across all treatments of the meta-analysis indicated that all parameters were sensitive with subcutaneous fat being the least sensitive, and 2) the prediction of fat in each depot, using the mean of the meta-analysis study as model inputs, were monotonically increasing indicating that all of the parameters are important determinants of model function.

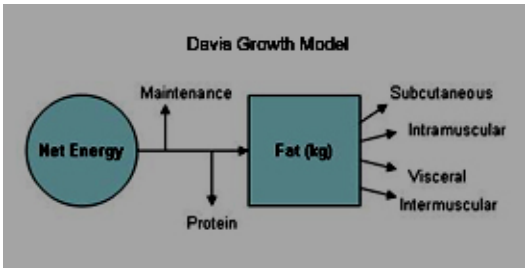

Figure 1. Partitioning of net energy in the Davis Growth Model to total body fat and then the partitioning of total body fat to 4 fat depots.

1. INTRODUCTION

The Davis Growth Model, a dynamic steer growth model (Oltjen et al., 1986) that includes 4 fat deposition models (Sainz and Hastings, 2000) is currently being used by the phenotypic prediction program of the Cooperative Research Centre (CRC) for Beef Genetic Technologies to predict 12/13th rib fat (mm) in beef cattle. The prediction of 12/13th rib fat (mm) has the potential to assist the beef industry meet stringent market specifications, both domestically and internationally, that are related to body weight (kg) and fat thickness (mm). Cattle frequently fall outside the market specifications and are therefore penalized. Predicting 12/13th rib fat at slaughter has the potential to assist producers meet stringent market specifications and increase profitability.

The concepts of cellular hyperplasia and hypertrophy are integral components of the Davis Growth Model. The net synthesis of total body fat is calculated from the net energy available after accounting for energy needs for maintenance and protein synthesis. Total body fat is then partitioned into 4 fat depots (intermuscular, intramuscular, subcutaneous, and visceral) (Figure 1). Three of the fat depots are then converted to carcass characteristics: intramuscular fat (IMF, kg) to IMF as a percentage (%), subcutaneous fat (kg) to 12/13th rib fat (mm), and visceral fat (kg) to kidney, pelvic, and heart fat (KPH, %) (McPhee et al. 2007a). The 4th fat depot, intermuscular fat, is not converted to any carcass characteristic. Each of the 4 fat depots is derived by a first order differential equation that was parameterized in acslXtreme using the data from a meta-analysis study (McPhee et al. 2006a).

The objectives of this study were: 1) describe the fat deposition first-order differential equations; 2) outline the steps in parameterizing the fat depots and; 3) discuss the sensitivity analysis of the parameters.

2. NOTATION AND UNITS

A number of symbols and special nomenclature are used throughout this paper. Table 1 outlines the notation with a description, units, and value where appropriate.

3. METHOD

The fat deposition models have been parameterized using acslXtreme (a tool for modelling and simulation of continuous dynamic systems and processes). The estimates of the parameter coefficients ($kFat_j$; (4)) for each of the fat depots, intermuscular, intramuscular, subcutaneous, and visceral were optimized against the simulated values of the first order differential equations (3) and the observed values of the initial and final fat (kg) for each of the fat depots. The initial and final fat (kg) were converted (McPhee, 2007a) from their carcass characteristics to their respective fat depots (kg) as described above.

Table 1. Description of mnemonics, variables and coefficients used in this study.

Item	Description	Units	Value
t	Time	Days	1 to # days on feed
j	Increment for each fat depot: intermuscular, intramuscular, subcutaneous, and visceral	-	1 2 3 4
ADS_{MAX}	Maximum adipocyte size	kg TG/kg DNA	4.5×10^5
DNA_j	Deoxyribonucleic acid	kg DNA	-
DNA_{MAX1}	Maximum DNA in intermuscular adipose	kg DNA	2.33×10^{-4}
DNA_{MAX2}	Maximum DNA in intramuscular adipose	kg DNA	1.00×10^{-4}
DNA_{MAX3}	Maximum DNA in subcutaneous adipose	kg DNA	2.00×10^{-4}
DNA_{MAX4}	Maximum DNA in visceral adipose	kg DNA	1.33×10^{-4}
EBW	Empty body weight	kg	-
$\beta(t)_j$	Proportion of total fat gain in each fat depot j at time t	-	-
Fat	Total body fat	kg	
F_j	Fat in each fat depot j	kg TG	-
K_{syn}	Protein synthesis coefficient	$kg^{0.27}$	-
K_{maint}	Protein maintenance coefficient	$Mcal.kg^{-0.75}.day^{-1}$	-
$kDNA_1$	DNA coefficient for intermuscular adipose	1/kg DNA	50
$kDNA_2$	DNA coefficient for intramuscular adipose	1/kg DNA	25
$kDNA_3$	DNA coefficient	1/kg	20

	for subcutaneous adipose	DNA	
$kDNA_4$	DNA parameter coefficient for visceral adipose	1/kg DNA	75
$kFat_j$	Fat parameter coefficient for each fat depot j	1/kg DNA	-
MEBW	Mature empty body weight	Kg	-
TG	Triacylglygcerol	Kg	-

The parameter coefficients ($kFat_j$) were estimated using the Nelder-Mead algorithm. Table 2 outlines the settings. The data were obtained from a meta-analysis study (McPhee et al. 2006a) consisting 165 mean values of carcass characteristics.

Table 2. Settings for the Nelder-Mead algorithm

Item	Value
Max iterations	1000
Expansion coefficient	2
Reflection coefficient	1
Contraction coefficient	0.5
Starting point step	0.2
Parameter stop tolerance	1E-05
Shrinkage coefficient	0.5
Objective function tolerance	1E-05

3.1 Frame Size

Frame size (1) was calculated based on the mean values of EBW reported in each of the publications in the meta-analysis study. The industry scale of frame size is 1 to 9 corresponding to 550 to 950 kg MEBW, in steps of 50 kg respectively, (BIF, 2002). Empty body weights of steers are adjusted to a stage of maturity based on the assumption of Fox and Black (1984) "that beef animals have equal body composition at similar stages of maturity". When data were not available to calculate frame size a scale was given based upon type of breed and the geographical location from which the steers were sourced.

$$\text{Frame size} = ((\text{MEBW, kg} - 750)/50) + 5 \quad (1)$$

MEBW is calculated based on a ratio (2) between reference (ref) values of EBW and MEBW (McPhee 2006b).

$$EBW/EBW_{ref} = MEBW/MEBW_{ref} \quad (2)$$

3.2 Fat Depot Equations

The fat (TG) deposition first-order differential equation (3) for each fat depot (F_j; j = intermuscular, intramuscular, subcutaneous, and visceral) is a proportion (4) of total body fat gain (kg/day). The DNA (kg; DNA_j) of each fat depot (5) is a variable in the calculation of the proportion (4). The proportion (4) is a function of adipocyte number (DNA) i.e., hyperplasia and ADS_{MAX} i.e., hypertophy.

$$\frac{dF_j}{dt} = \beta_j(t-1) \times \frac{dFat}{dt} \quad (3)$$

$$\beta_j(t) = kFat_j \times DNA_j(t) \times \left[1 - \left(\frac{F_j(t)}{DNA_j(t) \times ADS_{MAX}}\right)\right] \quad (4)$$

$$\frac{dDNA_j}{dt} = kDNA_j \times DNA_j(t) \times (DNA_{MAXj} - DNA_j(t)) \quad (5)$$

3.3 Parameterization

Two constraints were placed on the fat depot equations: $\sum\beta_j=1$ and the $\sum kFat_j=1$ at each point in time.

Five steps were taken to parameterize the model:

1. Parameter estimates of K_{syn} and K_{maint} for implanted and nonimplanted steers were optimized against body weight (kg) and total body fat (kg) so that the Davis Growth Model accurately predicted total body fat (kg) before total fat gain (kg/day) was proportioned into the 4 fat depots.

2. Then for each data source the following parameters were estimated:
   a. Subcutaneous fat ($kFat_3$).
   b. Intramusculat fat ($kFat_2$).
   c. Visceral fat ($kFat_4$).

Lastly, the intermuscular fat parameter ($kFat_1$) was calculated by difference (6).

$$kFat_1 = 1 - kFat_2 + kFat_3 + kFat_4 \quad (6)$$

3.4 Statistical Analysis

The intermuscular, intramuscular, subcutaneous, and visceral fat depot parameter coefficients were analyzed using the paired t-test procedure of SAS (SAS Inst., Inc., Cary, NC) for data normally

distributed and npar1way procedure, a non-parametric test for data not normally distributed.

3.5 Sensitivity Analysis

The sensitivity analysis of each fat deposition parameter coefficient ($kFat_j$) was evaluated in terms of: 1) the sum of squares across each of the 141 treatments from the meta-analysis study; and 2) the prediction of fat depots where the required inputs of the Davis Growth Model were set at the mean value of the meta-analysis data for implanted and non-implanted steers. Incremental changes of ± 10% to individual fat partition parameters were made with algebraic adjustments to the other parameters so that the 4 parameters summed to 1.

Sum of Squares

The residual (res_i) (7) using the meta-analysis data was calculated where y_i is the observed value from the meta-analysis data set and

$$res_i = \ln(y_i/Y_i) \quad (7)$$

Y_i the predicted value from the Davis Growth Model (3) for i = 1, 2, …, 141. The residual sum of squares (RSS_j) (8) was evaluated:

$$RSS_j = \sum_{i=1}^{141} res_i^2 \quad (8)$$

where j = 1 to 4 for each fat depot. The sum of the residuals of all depots was calculated as follows: $RSS = RSS_1 + RSS_2 + RSS_3 + RSS_4$, where RSS is the total sum of the residuals of each fat depot (i.e., RSS_1 is the residual sum of squares for intermuscular fat etc.). It is appropriate to sum the residuals, as described, when the error variance is not known in cases where experiments have not been replicated (p. 30 France and Thornley, 1984). The log transformation in res_i was used so that each residual (i.e., RSS_1, RSS_2, RSS_3, and RSS_4) was independent of any scaling factors and it is also assumed that each fat depot (F_1, F_2, F_3, and F_4) has the same coefficient of variation (p. 30 France and Thornely, 1984). Graphs are then plotted with the incremental changes to the parameter coefficient on the x axis and the residual sum of squares of the fat partition parameter under investigation on the y axis. A 'U' shaped graph indicates a parameter to which the model is sensitive.

Prediction of Fat Depots

Sensitivity of incremental changes to the parameter values were evaluated for each predicted fat depot (intermuscular, intramuscular, subcutaneous, and visceral) where the required model inputs were set at the mean value of the meta-analysis data for implanted and non-implanted steers. A curve with an increasing slope would indicate that the parameter is sensitive.

4. RESULTS AND DISCUSSION

4.1 Optimization

Twenty-four data sources failed to converge. The mean values of the fat depot parameters ($kFat_j$) reported in Tables 3 and 4 indicate that the effect of implant status and frame size, respectively are not significant. These results indicate that the depots are not metabolically different between frame sizes and implant status at the level of aggregation used to simulate fat deposition in beef steers.

Table 3. Effect of implant or non -implant status on fat depot parameter values (1/kg DNA)

Item	Implant		SE	*P*-Value
	Yes	No		
No. of samples	97	44		
Intermuscular[1]	0.1652	0.1415	-	-
Intramuscular	0.3462	0.3440	0.010	0.87[2]
Subcutaneous	0.2679	0.2743	0.035	0.62
Visceral	0.2207	0.2397	0.100	0.17

[1] Calculated by difference; parameters add to 1.
[2] Data normally distributed t-test ($P > |t|$).

Table 4. Effect of frame size classified as either small/medium or large on fat depot parameter values (1/kg DNA)

Item	Frame size Small/Med	Large	SE	*P*-Value
No. of samples	40	101		
Intermuscular[1]	0.1693	0.1532	-	-
Intramuscular	0.3409	0.3476	0.035	0.54[2]
Subcutaneous	0.2641	0.2721	0.014	0.55
Visceral	0.2256	0.2256	0.008	0.92

[1] Calculated by difference; parameters add to 1.
[2] Data normally distributed t-test ($P > |t|$).

4.2 Fat depots

Figure 2 illustrates the partition of 152 kg of total body fat into 4 fat depots. Figure 2 is a reasonable

representation of fat distributed in beef cattle. A preliminary analysis (McPhee et al. 2007b) indicates that the Davis Growth Model over predicts fat in all fat depots. Further work is required to improve the prediction of subcutaneous and intramuscular fats (kg). However, the results look promising and the prototype Davis Growth Model is a good first step in assisting the beef industry to predict fat deposition.

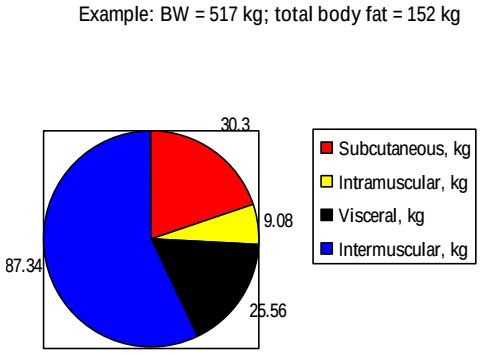

Figure 2. Example of total body fat (kg) partitioned into 4 fat depots (kg).

4.3 Sensitivity analysis

One hundred and forty one individual observations were simulated. The sum of squares sensitivity analysis shown in Figure 3 indicates that the subcutaneous fat parameter is the least sensitive followed by intramuscular fat, visceral fat, and lastly the intermuscular fat parameter. All fat depot parameters (Figure 3) are 'U' shaped indicating sensitivity to the model. The unadjusted parameter values (solid triangles) were not at the minimum because the remaining parameters were adjusted so that the parameters added to 1, as mentioned above. The effect of each partition parameter on the prediction of the respective fat depots (Figure 4) was monotonic increasing, indicating that the parameters are important determinants of model function. Intramuscular fat was shown to be the least important.

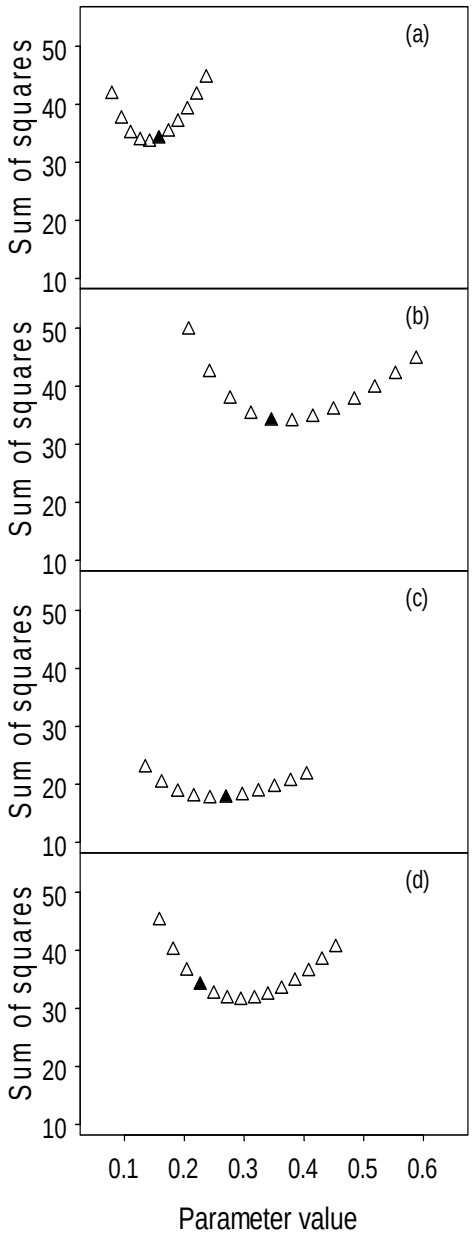

Figure 3. Sensitivity analyses for fat depot partition parameter effect on sum of squares of (a) intermuscular fat, (b) intramuscular fat, (c) subcutaneous fat, and (d) visceral fat (kg) (solid triangle represents default parameter value)

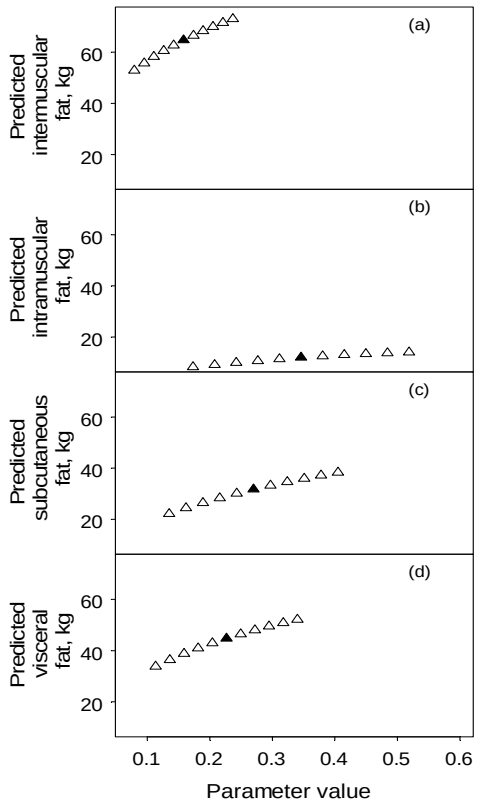

Figure 4. Sensitivity analyses for fat partition parameter effect on the fat depot prediction of (a) intermuscular fat, (b) intramuscular fat, (c) subcutaneous fat, and (d) visceral fat (kg) (solid triangle represents default parameter value)

5. CONCLUSIONS

acslXtreme, using the Nelder-Mead algorithm, estimated the parameters of the fat deposition models in the Davis Growth Model. The steps in the parameterization were outlined where the K_{syn} and K_{maint} parameters were estimated to accurately predict body weight (kg) and total body fat (kg) at slaughter. After K_{syn} and K_{maint} were estimated the subcutaneous fat parameter was the first parameter to be estimated followed by intramuscular and visceral fat parameters. Each of the fat depots was estimated against initial and final fat depots (kg) reported in the meta-analysis study (McPhee et al. 2006a).

The statistical analysis of the fat depot parameters indicated that the fat parameters are not metabolically different between frame size and implant status at the level of aggregation used to simulate fat deposition in beef steers. The sensitivity analyses indicated that the fat partition parameters are sensitive and important determinants of model function.

The Davis Growth Model is a net energy model that partitions total body fat gain (kg/day) into 4 fat depots after accounting for maintenance and protein gain. The results suggest that the prototype Davis Growth Model is a good first step in assisting the beef industry to predict fat deposition.

6. REFERENCES

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