Assessment of body fat composition in crossbred Angus × Nellore using biometric measurements¹

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ABSTRACT: This study was conducted to assess the body and empty body fat physical and chemical composition through biometric measurements (BM) as well as postmortem measurements taken in 40 F₁ Angus × Nellore bulls and steers. The animals used were 12.5 ± 0.51 mo of age, with an average shrunk BW of 233 ± 23.5 and 238 ± 24.6 kg for bulls and steers, respectively. Animals were fed 60:40 ratio of corn silage to concentrate diets. Eight animals (4 bulls and 4 steers) were slaughtered at the beginning of the trial, and the remaining animals were randomly assigned to a 1 + 2 × 3 factorial arrangement (1 reference group, 2 sexes, and 3 slaughter weights). The remaining animals were slaughtered when the average BW of the group reached 380 ± 19.5 (6 bulls and 5 steers), 440 ± 19.2 (6 bulls and 5 steers), and 500 ± 19.5 kg (5 bulls and 5 steers). Before the slaughter, the animals were led through a squeeze chute in which BM were taken, including hook bone width (HBW), pin bone width, abdomen width (AW), body length (BL), rump height, height at the withers, pelvic girdle length (PGL), rib depth (RD), girth circumference (GC), rump depth, body diagonal length (BDL), and thorax width. Additionally, the following postmortem measurements were obtained: total body surface

(TBS), body volume (BV), subcutaneous fat (SF), internal physical fat (InF), intermuscular fat, carcass physical fat (CF), empty body physically separable fat (EBF), carcass chemical fat (CFch), empty body chemical fat (EBFch), fat thickness in the 12th rib, and 9th to 11th rib section fat. The equations were developed using a stepwise procedure to select the variables that should enter into the model. The r^2 and root mean square error (RMSE) were used to account for precision and accuracy. The ranges for r^2 and RMSE were 0.852 to 0.946 and 0.0625 to 0.103 m², respectively for TBS; 0.942 to 0.998 and 0.004 to 0.022 m³, respectively, for BV; 0.767 to 0.967 and 2.70 to 3.24 kg, respectively, for SF; 0.816 to 0.900 and 3.04 to 4.12 kg, respectively, for InF; 0.830 to 0.988 and 3.44 to 8.39 kg, respectively, for CF; 0.861 to 0.998 and 1.51 to 10.98 kg, respectively, for EBF; 0.825 to 0.985 and 5.96 to 8.46 kg, respectively, for CFch; and 0.862 to 0.992 and 5.54 to 12.19 kg, respectively, for EBFch. Our results indicated that BM that could accurately and precisely be used as alternatives to predict different fat depots of F₁ Angus × Nellore bulls and steers are AW, GC, or PGL for CF estimation; HBW and RD for CFch estimation; and body lengths such as BL and BDL for InF and SF estimation, respectively.

Key words: biometric measurements, carcass composition, carcass prediction, empty body composition, empty body prediction, modeling

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INTRODUCTION

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The National Academies of Sciences, Engineering, and Medicine (2016) recommended that comparative slaughter trials for beef cattle research should be revisited to more accurately evaluate the retention of body energy.

Alternative methods to estimate body composition have been used (Hooper, 1944; Hankins and Howe, 1946; Kraybill et al., 1952; Powell and Huffman, 1973; Crouse and Dikeman, 1974; Clark et al., 1976; Byers, 1979), but some are rather limited due to changes in cattle growth over the years due to breeding programs, which might have somewhat changed nutrient requirements (Franke, 1980; Long, 1980; Marshall, 1994; May et al., 1994; Thornton, 2010; Loor et al., 2013; Bionaz, 2014; Haskell et al., 2014).

Some research groups have attempted to address body composition estimation without sacrificing entire carcasses and still assessing nutritional requirements. Most recently, the evolution diverted into body size scaling, as pointed out by Tedeschi and Fox (2016), where biometric measurements (**BM**) are used to improve the predictability of growth and finishing models. Fernandes et al. (2010) and De Paula et al. (2013) have developed predictive equations using BM for grazing *Bos indicus*; however, Fonseca et al. (2016) performed a thorough evaluation and concluded that only body volume and empty body physically separable fat equations could be used for F₁ Angus × Nellore cattle in feedlot conditions. Because there are no equations that use BM for crossbred animals fed a high nutrition level, we hypothesize that new BM-based equations should be developed to address such needs.

Therefore, the first objective was to measure and analyze biometrical growth and whole carcass and body composition. The second objective was to develop predictive equations based on BM to estimate body surface and volume, carcass fat composition, and empty body fat compositions of zebu-cross animals with an independent data set differing in plane of nutrition, breed, and sex.

MATERIALS AND METHODS

Humane animal care and handling procedures of the Federal University of Viçosa (Brazil) were followed in this research.

Location, Animals, and Diet Composition

Forty F₁ Angus × Nellore (21 bulls and 19 steers), with an initial age of 12.5 ± 0.51 mo and average shrunk BW (**SBW**) of 233 ± 23.5 and 238 ± 24.6 kg for bulls and steers, respectively, were used. The trial was conducted in a $1 + 2 \times 3$ factorial arrangement of treatments (reference group in addition to 2 sexes and 3 slaughter weights). The animals were randomly assigned into 4 slaughter weight-based groups: baseline, 380, 440, and 500 kg. The reference group was slaughtered at the beginning of the trial (4 bulls and 4 steers). The other groups were slaughtered when the group of

animals reached an average BW of 380 ± 19.5 (6 bulls and 5 steers), 440 ± 19.2 (6 bulls and 5 steers), and 500 ± 20 kg (5 bulls and 5 steers). The animals were housed in individual pens with concrete aprons and concreted feeders and bunks and placed in a total area of 30 m², of which 8 m² was sheltered. The diet was formulated according to Valadares Filho et al. (2006) to contain 11% CP. Animals were fed 60% corn silage and 40% concentrate. The concentrate was composed of corn, soybean meal, urea, ammonium sulfate, sodium chloride, limestone, and mineral mix. The animals were fed ad libitum twice daily (at 0600 and 1600 h) with a total mixed ration, and the intake was adjusted to maintain orts in a ratio of 5 to 10% of the offered as-fed diet. Water was available all the time.

Biometric Measures

The BM (Table 1) were taken 1 d before the slaughter, along with BW measurements, to obtain the full BW. The same technician was responsible for all BM taken during the trial. Animals were properly adapted to the squeeze chute prior to d 1 of the trial. Once in the squeeze chute, each animal was positioned upright and the BM were taken using specific anatomical locations as baseline points by hand palpation as recommended and adapted by Fisher (1975), Lawrence and Fowler (2002), Fernandes et al. (2010), and De Paula et al. (2013) with the aid of a large caliper (Hipometro tipo Bengala with 2 bars; Walmur Instrumentos Veterinários, Porto Alegre, Brazil) and a graduated plastic flexible tape. The BM included were hook bone width (**HBW**) as the distance between the 2 ventral points of the tuber coxae (large calipers); pin bone width as the distance between the 2 ventral tuberosities of the tuber ischia (large calipers); abdomen width (**AW**), measured as the widest horizontal width of the abdomen (paunch) at right angles to the body axis (large calipers); body length (**BL**) as the distance between the dorsal point of the scapulae and the ventral point of the tuber coxae (tape); rump height (**RH**), as measured from the ventral point of the tuber coxae, vertically to the ground (large calipers); height at the withers, measured from the highest point over the scapulae, vertically to the ground (large calipers); pelvic girdle length (**PGL**) as the distance between the ventral point of the tuber coxae and the ventral tuberosity of the tuber ischii (large calipers); rib depth (**RD**), measured vertically from the highest point over the scapulae to the end point of the rib, at the sternum (large calipers); girth circumference (**GC**), taken as the smallest circumference just posterior to the anterior legs, in the vertical plane (tape); rump depth, measured as the vertical distance between the ventral point of the tuber coxae and the ventral line (large calipers); body diagonal length

(BDL), measured as the distance between the ventral point of the tuber coxae and the cranial point of shoulder (tape); and thorax width (TW) as the widest horizontal width across shoulder region, at the back (large calipers).

Slaughter, Body Volume, and Total Body Surface

The animals were fasted for 16 h before slaughter to obtain the SBW. Animals were stunned with a non-penetrating stunner (model Leiser 1962; Equipamentos e Maquinas para Frigorifico Ltda, Batatais, São Paulo, Brazil) and killed by exsanguination using conventional humane procedures. The body volume (BV) was measured using a cylindrical, iron barrel filled with tap water (Fernandes et al., 2010; De Paula et al., 2013). At the moment that each animal was stunned, its body was lifted and submerged in the barrel with the head remaining outside the water. A translucent hose with a measuring tape attached inside was tightly and vertically connected to the outside of the barrel was used as. Then, the BV was computed using the distance the water was displaced and the radius of the water tank.

Blood was weighed and sampled (about 340 g), immediately oven-dried at 65°C for 72 h, ground, and stored for subsequent laboratory analysis. All the body constituents were cleaned and weighed: internal organs (lungs, heart, kidneys, trachea, liver, reproductive tract, and spleen), the digestive tract (rumen, reticulum, omasum, abomasum, and small and large intestines), KPH, visceral fat, tongue, tail, hide, head, limbs, and carcass. The total body surface (TBS) was determined by adapting the method described by Brody and Elting (1926), Fernandes et al. (2010), and De Paula et al. (2013) as follows: the TBS was measured immediately after slaughter and the removal of the hide, which was completely extended over a 2- by 2-cm gridded 3 by 3 m banner, and the coordinates (x,y) of the hide borders were taken and the area was computed using a regular integration process. Empty BW (EBW) was computed as the sum of all body constituents. The viscera and organs were ground together immediately after slaughter, subsampled, frozen, freeze-dried, and stored for subsequent analysis. Similarly, the hide, head, and limbs (1 anterior and 1 posterior) were sampled, frozen, dried, and stored for subsequent laboratory analyses. Internal physical fat (InF) was calculated as the sum of the KPH and the visceral fat.

Dissections

The individual carcasses were separated into 2 identical longitudinal halves. The half carcasses were weighed hot and chilled at -1°C. After a 24-h chill, the carcasses were reweighed to obtain the chilled carcass weight before the dissections. A section of the rib was

obtained by sawing the area between the 9th and 11th rib from the left carcass as described by Hankins and Howe (1946), and then the section was dissected into bone, muscle, and fat (9th to 11th rib section fat [HHF]) and properly weighed. The fat thickness in the 12th rib was obtained in the same left-half carcass. The rest of the left-half carcass was dissected and weighed as subcutaneous fat (SF), intermuscular fat, muscle, and bone and then summed with the 9th to 11th rib section weight and composition to account for the full left-half carcass. All components were weighed and sampled to determine chemical composition. The intermuscular fat and SF were summed to represent the total carcass physical fat (CF). The empty body physically separable fat (EBF) was calculated as the sum of the InF and CF contents.

Laboratory Analyses

Except for blood samples, which were dried at 60°C for 72 h, all other samples were freeze-dried for 72 to 96 h and partially defatted by washing them with petroleum ether in a Soxhlet extractor apparatus for approximately 6 h (Fernandes et al., 2010). The amount of fat extracted was computed by weight difference. All samples were ground using a ball mill (TE350; Tecnal Equipamentos Científicos, Piracicaba, Brazil) and analyzed for ether extract and DM. The remaining fat was extracted in an XT15 extractor (ANKOM Technology Corp., Macedon, NY) using XT4 filter bags as suggested by the American Oil Chemists' Society (2009) using petroleum ether as the solvent. The total chemical fat content was assessed by the summation of the 2 extractions, partial (Soxhlet extractor) and definitive (XT15 extractor). The amount of carcass chemical fat (CFch) and the empty body chemical fat (EBFch) was estimated by multiplying each component weight by its ether extract content.

Equations Development

Descriptive statistics and Pearson correlation coefficients of all variables utilized in the equations' development are presented in Table 1 and Table 2, prospectively

Prediction of Total Body Surface and Body Volume.

The technique used to develop theoretical equations to predict TBS and BV was adapted from Thompson et al. (1983) as described by De Paula et al. (2013), which considered that the animal's body has the shape of a cylinder and 2 parallel planes (base and top), beginning at the thorax and ending at the posterior junction of the buttocks. The TBS were computed as the surface area of the cylinder and volume of the cylinder, respectively, as shown in Eq. [1] to [5]. Equation [1] is the sum of the lateral body surface (Eq. [2]) and the surface of the

top and base of the cylinder (Eq. [3]). The radius of the body was calculated with the GC as shown in Eq. [4] and used to compute the BV, as shown in Eq. [5].

$$\text{TBS} = \text{LBS} + \text{Sbt}, \quad [1]$$

$$\text{LBS} = (2\pi \times \text{RB} \times \text{BL})/10^4, \quad [2]$$

$$\text{Sbt} = 2 \times [(\pi \times \text{RB}^2)/10^4], \quad [3]$$

$$\text{RB} = \text{GC}/2\pi, \text{ and} \quad [4]$$

$$\text{BV} = (\pi \times \text{RB}^2 \times \text{BL})/10^6, \quad [5]$$

in which TBS is the total body surface (m²; Table 1), LBS is the lateral body surface (m²; Table 1), BV is the body volume (m³; Table 1), RB is the radius of the body (cm), Sbt is the base and top (parallel planes) surface area (m²), $\pi = 3.1416$, and BL is the body length (cm; Table 1).

The predicted values of TBS or BV were regressed on the observed TBS or BV to adjust for body parts (e.g., limbs) that the assumption of a cylindrical body shape would not be able to account for. In addition, other empirical equations to predict TBS (Eq. [6], [7], and [8]; Table 3), and BV (Eq. [9], [10], and [11]; Table 3) were developed using SBW and BM.

Predictions of Fat Depots: Subcutaneous, Carcass, and Empty Body. Equations were developed using information obtained either in vivo (e.g., SBW) or post-mortem. The development of the equations was done in steps. First, variables associated with the deposition of physically separable depots were targeted: SF (Eq. [12], [13], [14], [15], and [16]; Table 4), InF (Eq. [17], [18], [19], and [20]; Table 4), CF (Eq. [21], [22], [23], [24], and [25]; Table 4), and EBF (Eq. [26], [27], [28], [29], [30], and [31]; Table 4). Then, chemical depots were next to be included in the statistical model: CFch (Eq. [32], [33], [34], [35], [36], [37], [38], and [39]; Table 5) and EBFch (Eq. [40], [41], [42], [43], [44], [45], [46], and [47]; Table 5). The purpose was to adjust for the variation not explained by SBW alone or to give an alternative source of estimation when direct measurements are constraints that may limit the availability of input information for the equations. Several equations were developed using SBW as the sole predictor (Eq. [7] and [10] [Table 3]; Eq. [12], [17], [21], and [26] [Table 4]; and Eq. [32] and [40] [Table 5]). Next, each fat depot was analyzed for its ability to be predicted either by HHF or through BM. If BM explained some of

Table 1. Description statistics of the data used to generate prediction equations

Item	No.	Mean	Maximum	Minimum	SD
Age, mo	40	16.08	19	12	2.4
BW, kg					
Full	40	414	603	232	100
Shrunk	40	407	589	225	99.8
Empty	40	370	541	199	93.7
Body characteristics					
Body surface, m ²	40	1.98	2.53	1.47	0.28
Body volume, m ³	40	0.38	0.55	0.21	0.10
Body density, kg/m ³	40	1,077	1,145	882	40.4
Body components					
Carcass, kg	40	233	336	122	62
FT, ¹ cm	38	5.03	11.6	0.40	3.27
Fat, kg					
Internal	40	18.9	37.6	4.05	9.63
Subcutaneous	40	6.61	15.6	1.03	3.67
Carcass	40	40	77.2	8.97	19.7
Empty body	40	58.9	114	13	28.9
HHF ²	40	0.91	1.82	0.18	0.49
Chemical fat, kg					
Carcass	40	45.9	90	14	20.2
Empty body	40	83.2	148	29.7	34.1
Body measurements, cm					
Hook bone width	40	44	52	35	4.57
Pin bone width	40	29.3	37.4	22	3.86
Abdomen width	40	54.9	68	40	6.21
Body length	40	135	160	89	22.1
Rump height	40	130	139	120	4.50
Height at withers	40	123	138	15.5	18.3
Pelvic girdle length	40	45.6	55	36	4.40
Rib depth	40	66.2	82	53	7.31
Girth circumference	40	173.6	199	136	16.6
Rump depth	40	48.6	55.5	41	3.72
Body diagonal length	40	98.7	111	85	6.63
Thorax width	40	41.3	52	28.5	6.18

¹FT = fat thickness in the 12th rib.

²HHF = 9th to 11th rib section fat.

the variation, then SBW was included to increase the power of prediction of the equations. The predicted SF theoretically could be obtained by the multiplication of the TBS by the fat thickness in the 12th rib and body density (Bieber et al., 1961; De Paula et al., 2013). The predicted SF was then first used to predict SF (Eq. [13]; Table 4). Then, the HHF was used as the only independent variable to estimate SF (Eq. [14]; Table 4). At the same time, the BM were used to SF (Eq. [15]; Table 4), and finally, BM and SBW were used together to increase the power of predictions (Eq. [16]; Table 4). The InF models were also adjusted to use HHF along with BM (Eq. [18]; Table 4), BM only (Eq. [19]; Table 4), or SBW along with BM (Eq. [20]; Table 4). The CF was assessed through HHF along with SBW (Eq. [22]; Table 4) or BM (Eq. [23]; Table 4), BM (Eq. [24]; Table 4), or

Table 2. Pearson correlation coefficients among the variables used in the development of the equations^{1,2}

	EBW	FT	InF	SF	CF	EBF	CFch	EBFch	HHF	TBS	BV	HBW	BL	RH	RD	GC	AW	PGL	BDL	TW
SBW	0.998	0.889	0.906	0.848	0.923	0.930	0.905	0.936	0.890	0.962	0.989	0.909	0.893	0.610	0.934	0.904	0.924	0.887	0.811	0.954
EBW	–	0.881	0.898	0.845	0.918	0.924	0.901	0.934	0.894	0.965	0.988	0.903	0.901	0.625	0.931	0.907	0.916	0.886	0.822	0.956
FT		–	0.890	0.918	0.942	0.936	0.915	0.928	0.901	0.834	0.888	0.861	0.783	0.555	0.894	0.786	0.808	0.822	0.757	0.867
InF			–	0.881	0.942	0.973	0.921	0.960	0.929	0.859	0.905	0.891	0.790	0.569	0.850	0.813	0.865	0.862	0.725	0.883
SF				–	0.961	0.947	0.890	0.914	0.928	0.800	0.841	0.803	0.767	0.612	0.832	0.782	0.791	0.726	0.822	
CF					–	0.994	0.952	0.972	0.946	0.884	0.916	0.865	0.804	0.582	0.889	0.847	0.857	0.834	0.761	0.880
EBF						–	0.954	0.981	0.953	0.887	0.925	0.885	0.810	0.586	0.888	0.847	0.871	0.854	0.759	0.893
CFch							–	0.984	0.905	0.851	0.898	0.869	0.814	0.555	0.881	0.805	0.812	0.842	0.794	0.871
EBFch								–	0.940	0.893	0.925	0.899	0.823	0.599	0.889	0.846	0.848	0.864	0.791	0.908
HHF									–	0.849	0.892	0.839	0.779	0.608	0.853	0.825	0.806	0.812	0.754	0.858
TBS										–	0.951	0.896	0.869	0.618	0.908	0.892	0.882	0.873	0.754	0.948
BV											–	0.887	0.891	0.610	0.929	0.892	0.910	0.877	0.811	0.934
HBW												–	0.866	0.556	0.867	0.849	0.860	0.903	0.782	0.926
BL													–	0.615	0.908	0.835	0.839	0.903	0.876	0.890
RH														–	0.602	0.524	0.572	0.615	0.549	0.578
RD															–	0.841	0.856	0.869	0.818	0.900
GC																–	0.840	0.783	0.776	0.867
AW																	–	0.830	0.706	0.894
PGL																		–	0.764	0.880
BDL																			–	0.781

¹Correlations followed by no superscript indicate $P < 0.001$.

²EBW = empty BW; FT = fat thickness in the 12th rib; InF = internal physical fat; SF = subcutaneous fat; CF = carcass physical fat; EBF = empty body physically separable fat; CFch = carcass chemical fat; EBFch = empty body chemical fat; HHF = 9th to 11th rib section fat; TBS = total body surface; BV = body volume; HBW = hook bone width; BL = body length; RH = rump height; RD = rib depth; GC = girth circumference; AW = abdomen width; PGL = pelvic girdle length; BDL = body diagonal length; TW = thorax width; SBW = shrunk BW.

SBW along with SF (Eq. [25]; Table 4). The EBF equations were adjusted to use either CF (Eq. [27]; Table 4) or HHF only (Eq. [28]; Table 4) or the combination of HHF and SBW (Eq. [29]; Table 4). Furthermore, 2 additional models were developed to estimate EBF considering only the BM (Eq. [30]; Table 4) or SBW along BM (Eq. [31]; Table 4). The CFch equations were adjusted to be used either with single predictors of SF (Eq. [33]; Table 5) and HHF (Eq. [34]; Table 5) or with a combination of predictors: BM (Eq. [35]; Table 5), SBW and SF (Eq. [36]; Table 5), SBW along with HHF (Eq. [37]; Table 5), HHF along with BM (Eq. [38]; Table 5), and SF along with BM (Eq. [39]; Table 5). Finally, the EBFch models were also adjusted to be used either with single predictors CFch (Eq. [41]; Table 5) and HHF (Eq. [42]; Table 5) or with a combination of predictors: SBW and SF (Eq. [43]; Table 5), SBW along with HHF (Eq. [44]; Table 5), BM (Eq. [45]; Table 5), SBW along with and BM (Eq. [46]; Table 5), and HHF along with BM (Eq. [47]; Table 5).

Statistical Analyses and Model Evaluation

Statistical Analyses. Statistical analyses were performed using SAS (SAS Inst. Inc., Cary, NC). Descriptive statistics were obtained with PROC MEANS and Pearson correlation coefficients among

variables were obtained with PROC CORR to evaluate which variables could explain the variation of fat depots. Linear regressions were developed to estimate TBS, BV, physical SF and InF, and physical and chemical CF and EBF with PROC REG. The STEPWISE and Mallows' Cp options were used in PROC REG to determine significant ($P < 0.05$) variables to be included in the statistical models. Outliers were tested by plotting the Studentized residual against the statistical model–predicted values. Data points were removed if the Studentized residual was outside the range of -2.5 to 2.5 . All interactions among variables and their quadratic effects were evaluated and removed from the statistical model if they were not significant at $P < 0.10$. The goodness of fit of the regression was assessed using the root mean square error (RMSE) and the r^2 .

Multicollinearity Diagnostics. All equations were evaluated regarding possible linear dependencies among variables included in the model. The evaluation was performed by comparing the variance increase in the parameters on each variable's addition into the model with the same situation but in an orthogonal scenario. The arbitrary coefficient adopted for diagnosis is based on the recommendations for the variance inflation factor from Chartterjee and Hadi (2012), who recommend a value larger than 10 as a threshold for biased estimation.

Table 3. Regression equations for predicting total body surface (TBS) and body volume (BV)¹

Equation no.	Equation ²	Statistics			
		No.	RMSE ³	<i>r</i> ²	<i>P</i> -value
TBS, m ²					
[6]	TBS = 0.89838 (0.007867†) + 0.33951 (0.02298†) × TBS _{cylinder}	40	0.103	0.852	<0.0001
[7]	TBS = 0.99436 (0.04926†) + 0.00256 (1.1759 × 10 ⁻⁴ †) × SBW	40	0.0733	0.924	<0.0001
[8]	TBS = 0.75066 (0.10189†) + 0.00184 (3.3783 × 10 ⁻⁴ †) × SBW + 0.01312 (0.00542*) × TW	39	0.0625	0.946	<0.0001
BV, m ³					
[9] ⁴	BV = 0.036 (0.016*) + 1.028 (0.049†) × BV _{cylinder}	28	0.016	0.942	<0.0001
[10] ⁴	BV = −0.011 (0.004*) + 9.8 × 10 ^{−4} (1.84 × 10 ^{−5} †) × SBW	34	0.00453	0.998	<0.0001
[11]	BV = −0.38922 (0.06323**) + 0.04549 (0.01501**) × HHF + 0.00470 (1.14 × 10 ^{−3} †) × RD + 9.5766 × 10 ^{−4} (4.5789 × 10 ^{−4} *) × GC + 0.00451 (1.23 × 10 ^{−3} †) × AW	39	0.022	0.949	<0.0001

¹Values within parentheses are SE of the parameter estimate.

²TBS_{cylinder} = Total body surface estimated based on the assumption that animal body has the shape of a cylinder; [TBS_{cylinder} = BLS_{cylinder} + Sbt, in which BLS_{cylinder} = $2\pi \times RB \times \text{body length (cm)}/10^4$, in which BLS_{cylinder} = lateral surface area (m²), and RB = GC/2 π , in which RB = radius of the body (cm), and Sbt = $2 \times (\pi \times RB^2)/10^4$, in which Sbt = the base and top (parallel planes) surface area (m²), and $\pi = 3.1416$]; SBW = shrunk BW (kg); TW = thorax width (cm); BV_{cylinder} = $\pi \times RB^2 \times \text{body length (cm)}/10^6$, in which BV_{cylinder} = body volume estimated based on the assumption that animal body has the shape of a cylinder; HHF = 9th to 11th rib section fat (kg); RD = rib depth (cm); GC = girth circumference (cm); AW = abdomen width (cm).

³RMSE = root mean square error.

⁴Equation devised by De Paula et al. (2013).

* $P < 0.05$; ** $P < 0.01$; † $P < 0.001$.

Evaluation of Predictive Equations. We obtained additional statistics to evaluate the predictive ability of the equations. The comparison of observed and predicted TBS, BV, and SF (theoretical equation) were realized using the reproducibility index or concordance correlation coefficient (CCC), which simultaneously accounts for accuracy and precision, and the RMSE of the prediction (RMSEP) as discussed by Tedeschi (2006). The accuracy for these comparisons was obtained by comparing the bias correction factor (Cb) and precision assessed by the r^2 , as recommended by Lin (1989). We assumed high accuracy and precision when coefficients were > 0.80 and low accuracy and precision when coefficients were < 0.50 .

RESULTS AND DISCUSSION

Descriptive Statistics and Correlation Analyses

There was no sex effect for any of the evaluated variables ($P > 0.055$). Animals were contemporaries and shared the same origin, producing a high homogeneity to the groups at the time of the random distribution. The animals were about 12 mo old at the beginning of the trial and reached up to 19 mo of age at the last slaughter group (500 kg). Because of the experimental design, the BW range was within 230 to 600 kg, similar to those of Fernandes et al. (2010) but heavier than those of De Paula et al. (2013). The average observed ratio between EBW and SBW was 0.909, similar to what has been reported elsewhere (0.891 by the NRC [2000] and 0.896 by Valadares Filho et al. [2006, 2010]). That is probably due to small variation of filling (Berg

and Butterfield, 1976) for animals fed this particular diet and due to the fact that yearling animals were slaughtered as the baseline group at the beginning of the trial when their thoracic cavity did not have the same holding capacity as the more mature animals. The average carcass yield or dressing percentage (DP) was 56.7%, excluding KPH, which is similar to observed values reported in the literature (Berg and Butterfield, 1976; Paulino, 2006; Marcondes, 2007). The removal of KPH is a common dressing procedure adopted in Brazil. In the United States, such difference may represent from 1 to 5% (Greiner et al., 2003), with DP values going high as 64.8% in the present data set. The EBF content in the empty body of the animals in the present data set was 2-fold the amount reported for grazing animals, as was the EBFch. The distribution within depots was similar to those reported by Fernandes et al. (2010) and De Paula et al. (2013). The kilograms of fat distributed along the fat depots was a lot greater (18.9, 40.0, 58.9, 6.61, 45.9, and 83.2 kg for InF, CF, EBF, SF, CFch, and EBFch, respectively; Table 1) than those observed for grazing animals (7.7, 20.1, 28.8, 5.2, 19.2, and 31 kg for InF, CF, EBF, SF, CFch, and EBFch, respectively; Fernandes et al., 2010; De Paula et al., 2013), but whenever the proportion is compared, the behavior pattern of fat deposition seem to be maintained. It is believed that the animals have the same patterns of deposition but differ in the amounts of deposited tissues (Fonseca et al., 2016).

The correlations between BM and physical and chemical characteristics were significant ($P < 0.01$), as were those between BV and TBS (Table 2). The high correlations should be interpreted as a possible linearity between BM and tissue depots along with the allometric

Table 4. Regression equations developed to predict subcutaneous, internal, carcass, and empty body physical fat¹

Equation no.	Equation ²	Statistic			
		No.	RMSE ³	r ²	P-value
Subcutaneous fat (SF), kg					
[12]	SF = -11.18801 (1.89620†) + 0.05781 (0.00455†) × SBW	38	2.81	0.812	<0.0001
[13]	SF = 4.8788 (0.85396†) + 0.08281 (0.00737†) × SFp	39	3.24	0.767	<0.0001
[14]	SF = 14.15103 (0.41974†) × HHF	39	2.7	0.967	<0.0001
[15]	SF = -43.85944 (4.21482†) + 0.46246 (0.11835†) × RD + 0.46976 (0.14568**) × AW	37	2.7	0.831	<0.0001
[16]	SF = 0.06442 (0.00576†) × SBW - 0.14071 (0.02434†) × BDL	38	2.84	0.957	<0.0001
Internal physical fat ⁴ (InF), kg					
[17]	InF = -16.7191 (2.77290†) + 0.08743 (0.00662†) × SBW	40	4.12	0.816	<0.0001
[18]	InF = -27.0780 (7.30185†) + 11.92453 (1.81319†) × HHF + 0.79717 (0.19571†) × HBW	40	3.04	0.900	<0.0001
[19]	InF = -65.78786 (6.33111†) + 1.19649 (0.27867†) × HBW + 0.58235 (0.20513**) × AW	40	4.06	0.822	<0.0001
[20]	InF = -40.12912 (7.83057†) + 0.07040 (0.01467†) × SBW + 1.08230 (0.28939†) × HBW - 0.12549 (0.05568*) × BL	39	3.27	0.887	<0.0001
Carcass physical fat (CF), kg					
[21]	CF = -31.52247 (4.38786†) + 0.17322 (0.01058†) × SBW	38	6.45	0.830	<0.0001
[22]	CF = -7.18645 (3.40523*) + 0.04725 (0.01381†) × SBW + 30.05248 (2.86083†) × HHF	36	3.44	0.984	<0.0001
[23]	CF = -17.16076 (8.09374*) + 33.89318 (2.2393†) × HHF + 0.46882 (0.17766*) × AW	37	3.64	0.988	<0.0001
[24]	CF = -131.65579 (13.16269†) + 1.62971 (0.59079†) × HBW + 1.50892 (36963†) × RD	40	8.39	0.874	<0.0001
[25]	CF = -13.33679 (3.17561†) + 1.72069 (0.15796†) × SF + 0.07623 (0.01144†) × SBW	40	3.78	0.981	<0.0001
Empty body physically separable fat (EBF), kg					
[26] ⁵	EBF = -16.8 (2.68†) + 0.142 (0.008†) × SBW	36	4.17	0.897	<0.0001
[27] ⁵	EBF = 1.445 (0.0103†) × CF	43	1.51	0.998	<0.0001
[28]	EBF = 6.17034 (2.26500†) + 56.37593 (2.20346†) × HHF	38	6.53	0.946	<0.0001
[29]	EBF = -13.53639 (4.63661**) + 0.08457 (0.01862†) × SBW + 41.36009 (3.83082†) × HHF	36	4.71	0.974	<0.0001
[30]	EBF = -190.33396 (17.21913†) + 2.66169 (0.77070**) × HBW + 1.98242 (0.47859†) × RD	39	10.9	0.848	<0.0001
[31]	EBF = 0.27818 (0.01915†) × SBW - 0.41650 (0.06148†) × RH	40	11	0.972	<0.0001

¹Values within parentheses are SE of the parameter estimate. Intercepts that were not different from 0 were removed from the final equation.

²SBW = shrunk BW (kg); SFp = predicted subcutaneous fat [kg]; SFp = total body surface (m²) × fat thickness in the 12th rib (cm) × 912/100; HHF = 9th to 11th rib section fat (kg); RD = rib depth (cm); AW = abdomen width (cm); BDL = body diagonal length (cm); HBW = hook bone width (cm); BL = body length (cm); RH = rump height (cm).

³RMSE = root mean square error.

⁴InF = KPH + visceral fat.

⁵Equation devised by Fernandes et al. (2010).

P* < 0.05; *P* < 0.01; †*P* < 0.001.

growth of the animals' body for the evaluated period. In other words, it explains that the measurements are increasing at the same moment and somewhat proportionally. The implications are that BM can be used to predict the growth and development of body fat depots in cattle regardless of the feeding system (feedlot or grazing). The HHF presented very high correlations among analyzed variables, indicating its importance for the prediction equations and even highlighting the importance of taking the 9th to 11th rib section as a reliable and relatively less expensive technique to be used to estimate body composition, an important measurement when nutrient requirements estimations are estimated. Among BM, the HBW, RD, GC, AW, and TW presented the highest correlations, indicating their importance in explaining the body composition, especially along with SBW, as exemplified by GC, 9th to 11th rib section (RD), and hindquarter length (AW and HBW). Among all BM, only height at the withers was not highly correlated with

the other variables analyzed. This is probably an indication that crossbred Angus cattle tend to present smaller variation in height at the withers than Nellore, with implication on growth characteristics with Angus cattle growth being more horizontal rather than vertical, which would be of interest from a meat production perspective.

Equations to Predict Total Body Surface and Body Volume

The TBS and BV predictions are presented in Table 3 (Eq. [6] and [9], respectively) and share the assumption that the body of a bovine has a cylinder shape.

Predicting Total Body Surface

Equation [6] (Table 3) was efficient in predicting the observed TBS, although with a significant intercept due to the age and size of the reference group. In yearling

Table 5. Regression equations to predict the carcass chemical fat (CFch) and empty body chemical fat (EBFch)¹

Equation no.	Equation ²	Statistic			
		No.	RMSE ³	r ²	P-value
CFch, kg					
[32]	CFch = −26.57832 (5.34680†) + 0.17635 (0.01285†) × SBW	39	7.87	0.831	<0.0001
[33]	CFch = 11.03675 (2.89406†) + 2.74138 (0.20448†) × SF	39	8.46	0.825	<0.0001
[34]	CFch = 9.24595 (2.29708†) + 39.18126 (2.19905†) × HHF	39	6.67	0.896	<0.0001
[35]	CFch = −124.58706 (11.16720†) + 1.48117 (0.50238**) × HBW + 1.58685 (0.31338†) × RD	38	7.04	0.866	<0.0001
[36]	CFch = −14.25500 (5.72338*) + 0.11260 (0.002067†) × SBW + 1.06169 (0.29013†) × SF	39	6.81	0.874	<0.0001
[37]	CFch = 0.04119 (0.00875†) × SBW + 31.16144 (3.50651†) × HHF	39	6.32	0.983	<0.0001
[38]	CFch = 36.22536 (2.42635†) × HHF + 1.18618 (0.41119**) × HBW − 0.23176 (0.10276*) × GC	39	6.13	0.985	<0.0001
[39]	CFch = −83.80479 (15.38547†) + 0.99235 (0.25591†) × SF + 1.03508 (0.30240**) × RD + 1.05872 (0.45477*) × PGL	38	5.97	0.904	<0.0001
EBFch, kg					
[40]	EBFch = −44.23711 (7.68119†) + 0.31118 (0.01847†) × SBW	39	11.31	0.882	<0.0001
[41]	EBFch = 7.95763 (2.20494†) + 1.63143 (0.04460†) × CFch	39	5.54	0.972	<0.0001
[42]	EBFch = 20.40204 (3.19200†) + 67.66538 (3.05578†) × HHF	39	9.27	0.928	<0.0001
[43]	EBFch = −22.86750 (7.92366**) + 0.19657 (0.02856†) × SBW + 2.01026 (0.39413†) × SF	40	9.43	0.924	<0.0001
[44]	EBFch = 0.09081 (0.01110†) × SBW + 49.99575 (4.4559†) × HHF	39	8.02	0.992	<0.0001
[45]	EBFch = −214.54508 (19.34077†) + 3.58432 (0.86318†) × HBW + 2.10080 (0.53683†) × RD	39	12.2	0.862	<0.0001
[46]	EBFch = −103.10948 (27.55943†) + 0.23388 (0.04474†) × SBW + 2.06942 (0.97643*) × HBW	40	11.6	0.884	<0.0001
[47]	EBFch = −55.21285 (19.73035†) + 51.00698 (5.03122†) × HHF + 2.06807 (0.53448†) × HBW	39	7.89	0.945	<0.0001

¹Values within parentheses are SE of the parameter estimate. Intercepts that were not different from 0 were removed from the final equation.

²SBW = shrunk BW (kg); SF = subcutaneous fat (kg); HHF = 9th to 11th rib section fat (kg); HBW = hook bone width (cm); RD = rib depth (cm); GC = girth circumference (cm); PGL = pelvic girdle length (cm).

³RMSE = root mean square error.

* $P < 0.05$; ** $P < 0.01$; † $P < 0.001$.

animals, it is expected that BL is in the early stages of growth (horizontal growth), but a 60% increase in the length of the body was observed. If measurements of TBS were to be taken in later stages of maturity, as shown by De Paula et al. (2013), the intercept would tend to be 0 and BL and GC as the predictors of TBS would be responsible for 57% of the variation in surface area. As the body grows, from yearlings to up to 18 mo of age, the cylindrical shape is responsible for 34% of TBS, with, again, GC in conjunction with BL being the most important BM affecting surface area and growth. The cooling rate of a body is highly dependent on the surface area, according to the Stefan-Boltzmann law. The change in surface area is known to affect nutrient requirements of mammals because heat loss and heat production have to be the same; if a difference in surface area holds true for *B. indicus* vs. *Bos taurus*, increments in length (BL) and thickness of the body (GC) could be associated with adaptive changes of the former for warmer and the latter for colder climate changes. High precision ($r^2 = 0.85$) and high accuracy ($C_b = 0.997$) and, therefore, a high reproducibility index ($CCC = 0.921$) was observed for TBS prediction. Despite the model's underestimation, the mean square error of prediction partitions partitions show that almost 100% of the error is random and, along with the small RMSE related to the observed means, is only 4.93%. Equation

[7] (Table 3), working with only SBW as an independent variable, did increase the precision ($r^2 = 0.924$) of the estimate and decrease the RMSE, which represented only 3.5% of the observed mean values. When combined, BM (TW) and SBW (Eq. [8]) increased the accuracy ($C_b = 0.999$) and precision ($r^2 = 0.95$) of the estimates. The partition of the errors showed a smaller RMSE and a reduction in its ratio compared with the average observed values. Therefore, the results indicate that Eq. [8] (Table 3) might be a better predictor of TBS than Eq. [7] (Table 3). The assumptions that the body has rather geometric shapes still allow one to predict TBS, although the measurements of SBW along TW are more feasible, accurate, and precise for such predictions. The combination of SBW and BM have been known to successfully increase the goodness of fit of those predictive equations (Brody and Elting, 1926; Pani et al., 1976; Fernandes et al., 2010; De Paula et al., 2013).

Predicting Body Volume

The BV predictions assume that the body of bovines has a cylindrical shape. Equation [9] (Table 3) was able to explain approximately 94% of the variation of the observed BV with a small RMSE of 0.0228 m³, with over 96% as a random component and a RMSEP of only 8.78%. Equation [9] (Table 3) was highly accurate ($C_b =$

0.99) and reproducible ($CCC = 0.94$). Alternatively, when BM was combined with HHF (Eq. [11]; Table 3), similar precision and accuracy were observed, showing that Eq. [11] (Table 3) could be used as an alternative rather than substitute equation. When SBW was the sole predictor (Eq. [10]; Table 3), precision ($r^2 = 0.99$) and accuracy and CCC increased (0.99 and 0.99, respectively), bringing the RMSEP down to a fraction of 3.6% of the observed values for the mean. It appears that there is a strong relationship between BV and SBW. The small variations in body density, regardless of the fat content, seem to indicate a pattern of tissue distribution of these animals, especially within trials.

The SBW is the best variable to explain variation in BW and could be used alone to predict the BV. It is possible, however, to use BM along with HHF or the TBS of the cylinder to estimate BV, although the latter does not increase the goodness of fit of the predictive equations.

Equations to Predict Subcutaneous Fat, Internal Fat, and Carcass and Empty Body Fats

Predicting Subcutaneous Fat. A large portion of the variability of SF (Eq. [12]; Table 4) was accounted for by SBW alone ($r^2 = 0.812$). Fernandes et al. (2010) and De Paula et al. (2013) also reported high precision (0.827 and 0.839, respectively) in predicting SF when SBW was the sole predictor. In the current study, each kilogram increase in SBW was reflected in a 58-g increase in SF. Fernandes et al. (2010) reported a relationship of 40 g SF/kg SBW and De Paula et al. (2013) reported a relationship of 22 g SF/kg SBW. Such difference is likely due to variation in animal characteristics, nutritional plane (Wright and Russel, 1984), and sex (Berg and Butterfield, 1976). The precision in predicting SF using the theoretical equation (Eq. [13]; Table 4) was high to intermediate ($r^2 = 0.77$ and $RMSE = 3.24$ kg), with 86% of the error being random. Equation [14] (Table 4), developed using only HHF as a predictor, was accurate ($C_b = 0.97$) and presented a good reproducibility index ($CCC = 0.85$). Equation [15] (Table 4), developed using only BM for the predictions, presented a similar precision ($r^2 = 0.83$ and $RMSE = 2.70$ kg), accuracy ($C_b = 0.98$), and reproducibility index ($CCC = 0.83$). The model comparison, on top of the main component of the error being random, indicates a similar goodness of fit for these 3 equations. An improvement was observed when SBW was used along with BDL (Eq. [16]; Table 4) and when HHF was used as a single predictor (Eq. [14]; Table 4). Both equations presented a reduced RMSE (2.7 and 2.84 kg for Eq. [14] [Table 4] and Eq. [16] [Table 4], respectively), maintaining either the same proportion (Eq. [16]; Table 4) or slightly less (Eq. [14]; Table 4) as random error and RMSEP proportional to the average observed.

Equation [14] (Table 4) was more accurate ($C_b = 0.99$) and reproducible ($CCC = 0.93$) than estimations from Eq. [16] (Table 4; $C_b = 0.97$ and $CCC = 0.83$).

In general, SF is quite difficult to predict because it has a lot of intrinsic variation in the amount deposited as well as in its partition (Aberle et al., 2012). Variations in the distribution of SF due to age (e.g., young animals) seem to be difficult to predict because of the small amount of it in the carcass (Fernandes et al., 2010). Additionally, other factors that may have contributed to variation in the SF pools are the plane of nutrition followed by potential tissue mobilization during compensatory growth, inherent factors for grazing system in the tropics, the effect of sex, and hormonal activity, among others (Aberle et al., 2012).

Predicting Internal Fat. Equations [17] to [20] (Table 4) were developed to estimate the InF content, which comprises visceral fat and KPH, in the animal's body. Equation [17] (Table 4) uses only SBW as an InF predictor and had an r^2 of 0.82 and RMSE of 4.12 kg. Equation [20] (Table 4) has HBW and BL included to improve InF prediction ($r^2 = 0.89$ and $RMSE = 3.27$ kg). An alternative equation (Eq. [19]; Table 4) was proposed in an attempt to estimate the InF using only BM (HBW and AW). A similar precision ($r^2 = 0.82$) and slightly smaller RMSE (4.06 kg) were observed, and 20.67% of the observed mean was due to the RMSEP. Also, Eq. [19] was highly accurate ($C_b = 0.996$) and reproducible ($CCC = 0.91$). Holloway et al. (1990) reported that ultrasonic measurement at the rib could be used to assess the fat depot over the visceral pool whereas the measurement at the rump could be to assess KPH fat depots. The BM selected by the stepwise procedure, AW, BL and HBW, are in agreement with the authors' assumption about the locations where InF growth pattern is best indicated.

Predicting Carcass Fat. All equations developed to predict CF (Eq. [21] to [25]; Table 4) were highly precise (r^2 values ranging from 0.83 to 0.99). The SBW alone accounted for 0.83 of the variation. It is understood from Eq. [21] (Table 4) that for each kilogram increment in the BW, about 173 g would be deposited as CF. An alternative prediction option would be to use HHF (Eq. [22]; Table 4). The 9th to 11th rib section has been a quite common procedure in nutritional requirements research (Tedeschi et al., 2004; Bonilha et al., 2011) and is feasible to obtain. Equation [22] (Table 4) was highly precise ($r^2 = 0.984$), accurate ($C_b = 0.99$), and reproducible ($CCC = 0.96$). The RMSE was mainly random and around 13.8% of the observed average CF. Then, AW was combined with HHF (Eq. [23]; Table 4), maintaining the similar goodness of fit ($r^2 = 0.988$, $C_b = 0.999$, $CCC = 0.956$, and $RMSE = 3.64$ kg). Also, 1 equation combining only BM (Eq. [24]; Table 4) was developed,

and the results were similar to those of Eq. [21] (Table 4), with an r^2 of 0.87, a RSME of 8.40 kg, and a nearly identical Cb of 0.99 and CCC of 0.91. Lastly, an equation was developed to predict CF, again using SBW but along with SF to increase the power of prediction (Eq. [25]; Table 4). The interpretation of Eq. [25] (Table 4) implies that a change in 1 kg of SBW would change 76 g in the CF whereas a change in 1 kg in SF would be followed by a change in 1.72 kg in CF. So CF predictions are much more sensitive ($1.72/0.076 = 22.6$ times) to changes in the SF depots than SBW itself. A possible constraint in using this equation would be the difficulty in accurately predicting the amount of SF due to a high number of factors that are likely to influence its deposition pattern, as mentioned above. Equation [25] (Table 4) seems more appropriate ($r^2 = 0.98$, RMSE = 3.78 kg, Cb = 1.00, and CCC = 0.98) when SF is actually measured or accurately estimated. The results suggest that SF can be a good predictor of CF and yet can be used to explain the variation not accounted for by SBW alone. Holloway et al. (1990) reported that GC is an important BM to explain variation in the distribution of fat, because it is related to all depots, except the percentage of total EBF in the soft tissues. Fernandes et al. (2010) also reported a better prediction of CF when BM were included in the model, especially AW. De Paula et al. (2013) found that RD and GC most affected the CF prediction. Our results suggest that live measurements of both AW and RD can be used when combined with either HHF or HBW (Eq. [23] and [24], respectively; Table 4) to predict CF.

Predicting Empty Body Fat. Equations developed to predict EBF (Eq. [26] to [31]; Table 4) were highly precise ($r^2 > 0.85$). This is probably because the carcass itself represented, on average, 62.7% of the EBW and CF corresponded to, on average, 68% of the EBF. Equation [26] (Table 4) was developed with SBW as the sole predictor of EBF, and it was able to account for approximately 86% of the variation in observed EBF. The SBW is also the most important variable for estimating EBF, with 269 g of increase for each kilogram of SBW gain. De Paula et al. (2013) reported 113 g/kg and Fernandes et al. (2010) observed 142 g/kg for the same ratio. These results illustrate how the plane of nutrition and the breed play a huge role in fat deposition and animal body composition. Theoretically, the difference between the 269 g/kg EBF and the 173 g/kg CF (Eq. [21]; Table 4) should be close to 87 g/kg InF (Eq. [17]; Table 4), considering the confidence interval of the SE of the parameters to be discounted. The actual prediction is that InF represents 9.6% of the SBW.

The inclusion of CF to predict EBF (Eq. [27]; Table 4) significantly increased the precision ($r^2 = 0.998$ and RMSE = 1.51) of the estimates and further suggested that for each kilogram increase in the EBF,

about 680 g is due to CF. These results are in agreement with the proportion of the EBF explained by CF observed in this trial. Equation [27] was highly accurate (Cb = 0.99) and reproducible (CCC = 0.99).

The next step was to add HHF as a predictor, either alone (Eq. [28]; Table 4) or along with SBW (Eq. [29]; Table 4). The HHF did increase the precision compared with Eq. [26] (Table 4; r^2 of 0.974 for Eq. [29] vs. a r^2 of 0.891 for Eq. [26]). Both equations were highly accurate (Cb > 0.998) and reproducible (CCC > 0.95). Additionally, HHF is a very sensitive fat depot that can be used as a predictive variable, and even though it represents only 1.8% of the EBF increase, its under- or overestimation is likely to alter EBF prediction 56 times more intensively. The observed values (Table 1) also suggest that approximately 70% of EBF was deposited as CF and 30% as InF. These values are in accordance with those reported by Ferrell and Jenkins (1984), Fernandes et al. (2010), and De Paula et al. (2013).

Then, equations composed by BM only (Eq. [30]; Table 4) or along with SBW (Eq. [31]; Table 4) were also developed. Equation [30] (Table 4) presented an average to high precision ($r^2 = 0.848$, RMSE = 10.86 kg) and was highly accurate (Cb = 0.987) and reproducible (CCC = 0.91). Lastly, the assessment of Eq. [31] (Table 4) confirmed an increment in the goodness of fit of both equations (Eq. [26] and Eq. [30]) by using SBW along with BM (RH). Equation [31] (Table 4) was highly precise ($r^2 = 0.972$), accurate (Cb = 0.997), and reproducible (CCC = 0.924). This fact supports the use of RH measurements as a good predictor of EBF, which is greatly responsible for variation in nutritional requirements that may affect optimal feeding strategies of animals fed in the same pen commonly used in sorting procedures for individual cattle management systems.

Development of Equations to Predict Chemical Fat in the Carcass and in the Empty Body

Predicting Carcass Chemical Fat. Similarly, the interpretation of equations developed to predict CFch (Eq. [32] to [39]; Table 5) has indicated that SBW seems to be a main predictive variable for its assessment. In general, all equations were highly precise. First, SBW was used as the sole predictor (Eq. [32]; Table 5). Equation [32] ($r^2 = 0.83$ and RMSE = 7.87) was highly accurate (Cb = 0.999) and reproducible (CCC = 0.889), further indicating that about 176 g/kg of SBW is CFch. Considering the average DP, 57%, observed in this trial, 101 g CFch/kg SBW can be estimated from the carcass, which is in close agreement with the 112 g/kg presented in Eq. [36]. For the average 407 kg SBW observed in this trial, the amount of predicted CFch would be 41 kg, which is close to the observed 45 kg. Additionally,

even though the minimum observed SBW was 225 kg (Table 1), which limits the inference to yearlings or heavy weaned calves, the interpretation of the negative intercept of the theoretical equation (Eq. [32]; Table 5) indicates that at 150 kg SBW, the animal has no CFch whatsoever. The implications are that those equations may lack the power to predict CFch for lighter animals; therefore, some research from the calving to weaning phases is necessary. Furthermore, as SBW decreases, the BM constitute a valuable asset for predictions because body fat depots at that stage are scarce, difficult to measure, and highly susceptible to error. In a simulation scenario, if the 3 groups maintained the observed DP, a 60-kg SBW difference between evaluated groups (380, 440, and 500 kg) would indicate that there is an increase of 22 kg CFch in the SBW during the finishing phase. Then, the predictions of CFch would be 40.43, 51.02, and 61.6 kg, which are closer to the observed values of 39.70, 53, and 66 kg. The biggest gap observed was for the 500-kg group, probably because those animals had higher DP. The practical implications rely on differences in animals that are likely to be in the same pen with totally different body chemical compositions. As SBW increases, the variability on CFch would be slightly greater, which means that heavier animals allocated within the same pen are more likely to have different body chemical compositions. Different body chemical compositions may have an impact on feed efficiency and nutritional requirements and increase variability within pens. Such scenarios weaken predictions because they are more likely to under- or overpredict days on feeding for the pen.

The following step was to adjust equations using other sole predictors such as SF (Eq. [33]; Table 5), HHF (Eq. [34]; Table 5), or BM (Eq. [35]; Table 5). The 3 equations were highly precise (r^2 of 0.825, 0.896, and 0.866, respectively), with a small RMSE (8.46, 6.67, and 7.04, respectively). Moreover, the equations were highly accurate ($C_b > 0.992$) and reproducible ($CCC > 0.90$). To improve precision and accuracy of Eq. [33] (Table 5), SBW was added as an explanatory variable (Eq. [36]; Table 5); it did not alter accuracy or reproducibility ($C_b = 0.994$ and $CCC = 0.928$) but slightly improved precision ($r^2 = 0.874$). When SBW was combined with HHF (Eq. [37]; Table 5), it substantially increased precision ($r^2 = 0.983$) and maintained a low RMSE (6.32 kg) and high accuracy ($C_b = 0.998$) and reproducibility index ($CCC = 0.914$).

Lastly, another 2 equations were developed (Eq. [38] and [39]; Table 5) using either SF or HHF along with BM. The addition of HBW and GC (Eq. [38]; Table 5) improved the precision of Eq. [34] (Table 5) from 89.6% to 98.5%. Concurrently, the accuracy (C_b from 0.992 to 0.998) and reproducibility index (CCC

from 0.897 to 0.914) were also increased. When SF is to be used as a predictor of CFch, RD and PGL may significantly improve predictability (Eq. [33]; Table 5). An increase in precision from 82.5% to 90.4% was observed along with an increase in the reproducibility index from 0.903 to 0.923, with constant yet high accuracy. The main BM influencing CFch were HBW and GC when used along with HHF and RD, and PGL when used along with SF. It seems that measurements of HHF along with SBW can provide a reliable estimation of CFch. If SF is somewhat available, it is recommended that RD and PGL measurements are taken to improve predictability of the equations. If researchers are to use HHF to estimate body composition, it is recommended that HBW and GC measurements be taken to improve predictability. Moreover, the results suggest that growth at the rump region either in width or length combined with growth in the depth of the ribs are great evidence of CFch growth.

Predicting Empty Body Chemical Fat. All equations (Eq. [40] to [47]; Table 5) were highly precise ($r^2 > 0.86$) in estimating EBFch. Equations [40], [41], and [42] were adjusted using single independent variables as SBW, CFch, and HHF. The equations were highly precise (r^2 of 0.882, 0.972, and 0.928, respectively) and accurate ($C_b = 0.999$), presenting a very good reproducibility index ($CCC > 0.939$). Per Eq. [40], about 311 g/kg of SBW is EBFch. For a cross-bred F_1 Angus $\times$ Nellore, an animal with an average EBFch pool of 83.22 kg would have to weigh around 409 kg, similar to the observed 407 kg. The animals used by Fernandes et al. (2010) started significant fat deposition at between 100 and 128 kg, whereas the animals used by De Paula et al. (2013) started at 68 to 76 kg. This is an indication that when those animals have started suffering from a nutrient restriction, they initiate fat deposition earlier once refeeding has occurred. Animals that were not significantly depositing chemical fat in relation to their growth were growing at normal rates and more likely to be weaned heavier (Hornick et al., 1998; Heyer and Lebret, 2007).

For Eq. [41] (Table 5), the authors used CFch as the sole predictor of EBFch. Equation [41] turned out to be highly precise ($r^2 = 0.972$) and had a small RMSE (5.54). Also, the equation was highly accurate ($C_b = 0.999$) and reproducible ($CCC = 0.983$). The equation also indicates that CFch represents 60% of the EBFch, which is in close agreement with the observed value (55%). Equation [42] (Table 5) was developed to use HHF as sole predictor and was highly precise ($r^2 = 0.928$), accurate ($C_b = 0.999$), and reproducible ($CCC = 0.939$). Shrunk BW was then combined with SF in Eq. [43] (Table 5) and was precise, accurate, and reproducible but did not improve the SBW prediction

when used alone. Then, SBW was combined with HHF (Eq. [44]; Table 5), which increased precision ($r^2 = 0.992$ vs. 0.882), accuracy ($C_b = 0.999$), and reproducibility ($CCC = 0.959$). Additionally, BM were used as sole predictors (Eq. [45]; Table 5) or along with SBW (Eq. [46]; Table 5) and HHF (Eq. [47]; Table 5). The equations were precise, accurate, and reproducible, but only Eq. [47] (Table 5) improved the power of prediction ($r^2 = 0.945$, $C_b = 0.999$, and $CCC = 0.960$) of Eq. [40] (Table 5). The main BM influencing EBFch were HBW when used along with HHF and both RD and HBW when used alone. The BM can be used to estimate EBFch with high precision and accuracy. Alternatively, HHF can be taken to estimate EBFch for assessing body composition, although it is recommended that HBW be taken in conjunction with EBFch to improve predictability. Moreover, the results suggest that growth at the rump region in width and growth of the ribs in depth, which are often combined, are great evidence of EBFch growth.

In conclusion, our results suggested that BM can be used as a tool to predict TBS, BV, SF, InF, CF, EBF, CFch, and EBFch either alone or in association with SBW and with other postmortem body characteristics that might increase the precision as well as the accuracy of prediction equations of confined F_1 Angus $\times$ Nellore bulls and steers. The AW, GC, or PGL could be used to estimate CF; HBW and RD could be used to estimate CFch; and body lengths such as BL and BDL could be used to estimate InF and SF, respectively. Because of the changes in composition that might occur in the body due to breed, sex, age, and nutritional practices, the equations developed in this study are recommended to be used under similar conditions. Further studies should evaluate the use of these equations and BM under different production systems and breed compositions.

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