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Research article

Estimation of body and carcass composition of crossbred growing bulls from 11th rib dissection

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ABSTRACT

Precise methods for measuring livestock body and carcass composition are essential for both animal and meat scientists. The aim of this study was to calibrate the 11th rib cut dissection method for the estimation of crossbred beef-on-dairy bull empty body (**EB**) and carcass compositions against reference tissue and chemical *postmortem* measurements. Sixty-six (66) crossbred bulls from Angus, Limousin and Simmental sires (n = 22 each) crossed on Brown Swiss dams were serially slaughtered along growth from 58 to 534 kg BW. The muscle, adipose tissue and bone contents of the left 11th rib were determined by physical dissection. Linear regressions followed by leave-one-out-cross-validation were tested between rib dissection variates (with or without additional ones: BW or carcass weight, carcass grading or *postmortem* linear measurements) and reference EB or carcass chemical (water, lipids, proteins, minerals and energy) and tissue (muscles, adipose tissues and bones, only for final slaughter group of 514 ± 12 kg BW, n = 30) compositions. When all bulls are considered (serial slaughter group, n = 66), the inclusion of rib dissection variate together with BW or hot carcass weight allowed precise estimations of EB and carcass masses and proportions of water [$R^2 \geq 0.91$, residual CV (**rCV**) $\leq 3.1\%$], lipid ($R^2 \geq 0.88$, rCV $\leq 14.0\%$), protein ($R^2 \geq 0.23$, rCV $\leq 3.7\%$) and energy ($R^2 \geq 0.89$, rCV $\leq 7.7\%$). Slight further improvements in precision were achieved when carcass grading conformation or fat scores was added to the multiple estimative regressions. Crossbreed effect was significant on the intercept of most of the predictive equations. Especially ×Angus had higher intercepts for lipids, energy and adipose tissues and lower ones for water, proteins and muscles, when compared to ×Limousin and ×Simmental. Further developments using for example rib imaging analysis rather than physical dissection may contribute to large scale and high-throughput phenotyping of body and carcass compositions.

Implications

Body chemical composition defines the nutritional needs of cattle, and carcass tissue composition is linked to its commercial value. Therefore, the estimative equations of body and carcass compositions based on the 11th rib cut dissection calibrated in the present study are valuable for both animal physiologists and meat scientists. This method does not entail any specific equipment or consumable cost, but professional butcher skills and around 15 minutes per rib dissection. Inclusion of the type of cattle (crossbreed) into the equations is required for improving the precision of the prediction.

Specification table

Subject	Physiology and Functional Biology
Type of data	Table, Figure
How data were acquired	Weighing bulls, carcasses, dissected organs and tissues with electronic scales. Laboratory analyses in duplicate of DM (3 h at 104 °C), minerals (furnace 550 °C until constant weight), lipids (ISO 6492:1999, petroleum ether extraction with a Büchi Speed Extractor E-916, Flawil, Switzerland), proteins (ISO 16634-

(*continued on next page*)

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	1:2008, N × 6.25 by Dumas combustion – thermal conductivity with a Leco Trumac CNS, St. Joseph, Michigan, USA), and energy (ISO 9831:1998, adiabatic calorimetry with an oxygen bomb calorimeter, AC600 LECO, Mönchengladbach, Germany).
Data format	Raw, processed and calculated data in Excel and reported results as tables and figures.
Parameters for data collection	Sixty-six (66) young bulls crossbred from a Brown Swiss cow inseminated with an Angus, Simmental or Limousin sire were fed with different total mixed rations. In a first trial, 18 (6 per crossbreed) had an average daily gain of 1.62 ± 0.18 kg/d from 169 to 512 kg BW, until slaughter at 472 ± 7 (n = 6) or 524 ± 7 kg BW (n = 12). In a second trial, 48 (16 per crossbreed) had an average daily gain of 1.49 ± 0.13 kg/d from 154 to 517 kg BW, until slaughter at 72 ± 10, 163 ± 5, 258 ± 12, 347 ± 11, 421 ± 8 (n = 6 each), or 507 ± 10 kg BW (n = 18).
Description of data collection	Data were collected by weighing living bulls before slaughter, weighing *postmortem* carcasses, tissues and organs, dissection and weighing of carcass and 11th rib cut tissues, grinding and chemical analyses on the homogenates of blood, hide, half-carcass and rest of empty body.
Data source location	Institution: Agroscope City/Town/Region: Posieux, Fribourg cantonal state Country: Switzerland Latitude and longitude for collected samples/data: 46.769, 7.105
Data accessibility	Repository name: Data INRAE Data identification number: https://doi.org/10.57745/EK4FFP Include Supplementary Tables S1 and S2.
Related research article	No research article is related to this article.

Introduction

Precise methods for measuring and predicting livestock body and carcass composition are essential in both animal and meat sciences. Access to such phenotypic data may improve farming system profitability. Body nutrient (lipids, proteins, minerals and energy) accretion in growing beef cattle is a major determinant of feed efficiency (Kenny et al., 2018) and animal robustness (Friggens et al., 2017). Besides, grading, and concomitantly, commercial value of beef carcass is linked to its tissue composition (proportions of muscles, adipose tissues and bones; Monteils et al., 2017). Reference measurements (so-called "gold standard") of empty body (**EB**; e.g. full body without digesta and urine) and carcass compositions require slaughtering animals, and then physical dissection for tissue composition, or grinding, homogenisation and laboratory analyses for chemical composition. Obviously, such *postmortem* procedures are costly, time-consuming and destructive of edible meat and offals. Several alternative methods were developed over the past century (Robelin, 1973; Scholz et al., 2015; Lerch et al., 2021). Among those, the use of single or multiple rib cut tissue or chemical composition variates was tested against reference EB or carcass compositions. Predictive equations were developed from 6th, 8th or 11th single rib cut (Robelin and Geay, 1975a and 1976; Robelin et al., 1975; Fiems et al., 2005) or from 9-11th multiple ribs cut (Hankins and Howe, 1946; Berndt et al., 2017). These former works highlighted the high precision of such method, and further slight improvements, when additional *postmortem* predictive variates were included (e.g., carcass grading score, morphological measurements, weights of dissectible tissues or organs; Robelin and Geay, 1975b and 1976; Fiems et al., 2005). Nonetheless, relationships between rib dissection variates and carcass composition were affected by the type of cattle studied. Especially, Robelin and Geay (1975b and 1976) reported specific intercepts depending on the breed of bull (i.e., Friesian, Charolais, Limousin and Salers) for multiple linear predictive equations of carcass tissue and chemical compositions from 6th or 11th rib dissection, similarly to Alhassan et al. (1975) on Hereford and Angus steers comparison based on 9–11th ribs cut. In addition, the rib cut dissection method was rarely calibrated for crossbred cattle. To our knowledge, only Berndt et al. (2017) evaluated in crossbred bulls (i.e. Nellore × Canchim, Angus or Simmental) the 9–11th ribs cut for predicting EB and carcass chemical compositions. Unfortunately, the general equations Berndt et al. (2017) reported merge all genetic groups. Therefore, suitability of the rib dissection method in beef-on-dairy crossbred cattle, and the putative effect of the sire beef breed on the estimative relationships have still to be established. Crossbred animals from dairy herds are common, and indeed, they are the most used in specialised fattening beef production systems in several countries (e.g. Ireland; Kearney et al., 2022; Switzerland; Lerch et al., 2020). Besides, there is a growing interest in beef-on-dairy crossbred cattle for beef meat production regarding economic outcomes and environmental implications (Berry, 2021; Faverdin et al., 2022).

The aim of this study was to calibrate the 11th rib cut dissection method for the estimation of beef-on-dairy crossbred bulls EB and carcass compositions against tissue and chemical reference *postmortem* measurements. Equations from Angus, Limousin and Simmental sires crossed on Brown Swiss dams were established along growth paths from 58 to 534 kg BW.

Material and methods

Animals

The study was performed at the experimental barn and slaughterhouse of Agroscope Posieux (Switzerland) and involved 66 young bulls purchased at the age of 31 ± 7 (mean ± SD) days in Swiss commercial dairy farms. Bulls were crossbred from a Brown Swiss dam inseminated with an Angus, Limousin or Simmental sire (n = 22 of each). Eighteen (6 per crossbreed) were part of a first experiment involving a total of 90 bulls fed with two different iso-energetic maize silage-based total mixed rations (**TMRs**, average daily gain of 1.62 ± 0.18 kg/d from 169 to 512 kg BW) until slaughter at either 472 ± 7 (n = 6) or 524 ± 7 kg BW (n = 12, final slaughter group). The remaining 48 (16 per crossbreed) were part of a second experiment involving a total of 102 bulls fed with two different iso-energetic TMRs based on maize and grass silages (average daily gain of 1.49 ± 0.13 kg/d from 154 to 517 kg BW). They were serially slaughtered at 72 ± 10, 163 ± 5, 258 ± 12, 347 ± 11, 421 ± 8 (n = 6 each, serial slaughter group), or 507 ± 10 kg BW (n = 18, final slaughter group). Crossbreed was balanced at all slaughter points.

Slaughter procedures, body, carcass and 11th rib measurements

After being deprived of feed from 00:00 h, bulls were slaughtered between 08:00 and 11:00 h by stunning with captive bolt followed by exsanguination, in accordance with legally defined procedures (Order 455.1 of Swiss federal laws, 2008). The head, tail, lower legs, hide and all the internal organs were removed, before the carcass was split into two halves along the spinal column as described in detail by Xavier et al. (2022).

Weights and morphological measurements

Bulls were weighed before (preslaughter BW) and after exsanguination. Half-carcasses were weighed hot and cold after chilling at 4 °C for 24 h. The weights of the left rear and front metacarpus (i.e., cannon) bones and of the perirenal adipose tissue were recorded. The bladder was weighed full and empty. The full digestive tract was separated into reticulo-rumen, omasum, abomasum, intestines, and omental and mesenteric adipose tissues. Each digestive tract section was further emptied and weighed again, in order to compute by a difference in the digestive content mass. Empty BW was computed from preslaughter BW minus the digestive content and urine weights. Blood weight was defined as the sum of exsanguinated blood (difference between pre- and postexsanguination weights) plus the difference between EB weight and the sum of every EB compartments weighed separately.

Cold carcass was graded by a single trained operator on a scale of 1–5 for fat and conformation scores, according to the CH-TAX classification system (Order 916.341.22 of Swiss federal laws, 1999, last update 2003; Proviande, 2005; for conformation score, the following numerical conversion was performed: C = 5, H = 4, T+ = 3.5, T = 3, T− = 2.5, A = 2 and X = 1), and the left cold half-carcass was measured for thigh thickness at the pubic symphysis, and hook-symphysis length (Robelin et al., 1975). The thicknesses of the subcutaneous adipose tissue and of the *longissimus thoracis* muscle were measured between the 11^{th} and 12^{th} left ribs using a calliper.

Carcass and 11^{th} rib tissue composition

Composition of each half-carcass was assumed to be equal. Further dissection and chemical analysis were then performed on the left half-carcass only. The day after slaughter, the 10^{th}–12^{th} rib section was removed from the cold left half-carcass. The section was defined by a parallel line to the spine axis passing through the point of the ilium and reaching straight to the 5^{th} intercostal space. The 11^{th} rib cut was separated at the exact intercostal mid-distances between 10^{th}–11^{th} and 11^{th}–12^{th} ribs (Geay and Beranger, 1969). Rib was then weighed and physically dissected by a professional butcher, before the respective weights of muscles (*longissimus thoracis* muscle and other muscles), adipose tissues (subcutaneous and intermuscular), and bones (including a slight portion of ligaments and tendons) were measured. Similarly, a physical dissection was performed by trained professional butchers on the total left cold half-carcass for the final slaughter group (n = 30), and the respective weights of muscles, adipose tissues (subcutaneous, internal and intermuscular), bones, and ligaments and tendons were recorded.

Empty body and carcass chemical composition

Blood samples (2 × 250 g) were collected at exsanguination, clotted at ambient temperature and stored at −20 °C pending chemical analyses. On the day of slaughter, the rest of EB (without exsanguinated blood and carcass) was fully collected in plastic boxes and stored at −20 °C. Similarly, the day after slaughter, immediately after the physical dissection (see above), the cold left half-carcass (including dissected 11^{th} rib) was fully collected and stored at −20 °C. In the first experiment, hide was combined with the rest of EB compartment, whereas in the second experiment, it was treated separately. Frozen half-carcass, rest of EB and hide (only in the second experiment) were ground separately using first an industrial crusher (Granulator type PS 4–5, Pallmann Industries, Pompton Plains, USA), followed by homogenous mixing (Mixer type MIX 165, Talsa, Spain) and grinding again using a cutter device (Cutter DMK 45C, DMS-Maschinensysteme, Saarbrücken, Germany). One kg sample of each homogenate compartment was frozen (−20 °C), before being finely minced again (Mincer type TWK 98, Kolbe foodtech, Elchingen, Germany). Two 250 g aliquots were ultimately sampled and frozen (−20 °C) pending chemical analyses.

Frozen homogenous aliquots of blood, half-carcass, rest of the EB and hide were lyophilised and finely ground with liquid nitrogen using a knife mill (Grindomix GM200, Retsch, Haan, Germany). Laboratory DM (3 h at 104 °C), mineral (furnace 550 °C until constant weight), lipid (ISO 6492:1999, petroleum ether extraction with a Büchi Speed Extractor E-916, Flawil, Switzerland), protein (ISO 16634-1:2008, N × 6.25 by Dumas combustion – thermal conductivity with a Leco Trumac CNS, St. Joseph, Michigan, USA), and energy (ISO 9831:1998, adiabatic calorimetry with an oxygen bomb calorimeter, AC600 LECO, Mönchengladbach, Germany) contents were further determined in duplicate. Intra-assay CVs for duplicate determinations for carcass were of 0.57, 0.03, 3.35, 0.47, 0.52 and 0.58% and for rest of EB, values were equal to 0.38, 0.04, 5.00, 0.63, 1.63 and 0.88% for lyophilisation DM, laboratory oven DM, mineral, lipid, protein and energy contents, respectively. The left hot half-carcass chemical proportions were applied at the right hot half-carcass to obtain the whole hot carcass composition in masses. Chemical composition of the EB was defined as the sum of the chemical composition reconstituted for the whole hot carcass with the ones of the rest of the EB, the hide (only separated from rest of EB in experiment 2) and the blood. Constant weighing and reweighing procedures before and after every cooling and freezing steps were ensured, and any weight loss from the initial weighing at the slaughterhouse was assumed to be water loss.

Statistical analyses

All statistics were performed with R software (version 3.6.3, R Core Team, 2020). Simple and multiple linear regressions were performed with the "lm" function (R package "stats", R Core Team, 2020) to estimate reference tissue and chemical compositions of EB and carcass from the 11^{th} rib cut dissection and *postmortem* morphological variates. The backward selection process was applied based on type 3 ANOVA to define variates of interest and significant ($P < 0.05$) or tendency ($0.05 < P \leq 0.10$) variates were selected. The effect of sire breed (Angus, Limousin or Simmental) was tested on intercept of regressions and reported whenever significant. Equations with better estimations than those with BW or hot carcass weight (**HCW**) alone were calibrated and further validated with a leave-one-out-cross-validation performed with the R package "caret" (Kuhn, 2021). The means bias (**MB**) used to evaluate the model accuracy was computed as follows (Tedeschi, 2006):

$$Mean\ \ bias = \frac{\sum(observed - predicted)}{n}$$

The model efficiency (**MEF**) evaluated the proportion variation which was explained by the model was calculated according to the formula reported in Tedeschi (2006):

$$Efficiency = 1 - \frac{\sum(observed - predicted)^2}{\sum\left(observed - \frac{\Sigma observed}{n}\right)^2}$$

Lin's concordance correlation coefficient (**CCC**) evaluates both precision and accuracy (Tedeschi, 2006) and was processed with the "CCC" function of the "DescTools" R package (Signorell et al., 2022).

Results

Postmortem body and carcass compositions

The body and carcass weights and composition, as well as anatomical measurements, are reported in Table 1. The BW was of 391 ± 154 and 514 ± 12 kg and the EB weight of 351 ± 140 and 464 ± 13 kg for the serial and final slaughter groups, respectively. Accordingly, the digestive content proportion into BW was of 10.2 ± 2.9% for serial and 9.8 ± 0.9% for the final slaughter group. Hot carcass weight averaged 220 ± 90 and 293 ± 13 kg corresponding to a carcass yield of 56.1 ± 2.7 and 57.1 ± 1.6% for serial and final slaughter groups, respectively. Both EB and hot carcass were mainly composed of water (62.8 ± 2.4% and 63.8 ± 2.3% in final slaughter group EB and hot carcass, respectively), followed by proteins (18.5 ± 0.8% and 18.5 ± 0.7%), lipids (15.4 ± 3.2% and 13.5 ± 3.0%) and minerals (3.5 ± 0.3 and 4.0 ± 0.4%). Hot carcasses of the final slaughter group were composed mostly of muscles (63.3 ± 3.2%), followed by bones (17.2 ± 1.2%) and adipose tissues (14.1 ± 3.1%). Final slaughter ×Angus crossbred bull EB and carcass presented consistently a higher content in lipids (18.9 ± 1.7 and 16.8 ± 1.8%, respectively) and in adipose tissues for the carcass (17.3 ± 2.5%) than ×Limousin (14.3 ± 2.1% for EB lipids, 12.5 ± 2.0% for carcass lipids and 13.0 ± 1.9% for adipose tissues) and ×Simmental (12.9 ± 1.8, 11.3 ± 1.7 and 11.9 ± 1.8%) crossbreeds (n = 10 for each crossbreed, Table 1).

Based on lipid-free EB or carcass, proportions of water, proteins and minerals were fairly constant among all 66 serial slaughter bulls (e.g., 73.5–77.0% and 72.8–76.5% water in lipid-free EB and carcass, respectively). Accordingly, water and lipid proportions were closely and negatively related ($r \leq -0.98$) with same slopes but slightly lower intercept for carcass than for EB (Fig. 1).

Estimation of empty body and carcass component masses

The most precise simple and multiple linear regression equations for the estimation of water, lipid, protein, mineral masses and energy content are reported for EB in Table 2 and for carcass in Table 3. Equations A denotes simple regressions with BW (for EB) or HCW (for carcass) as single predictive variate, whereas B–D are multiple regressions with BW or HCW and 11th rib dissection variates (B), together with carcass classification (C) or *postmortem* anatomical measurements (D). Statistics of regression models goodness-of-fit reported below originated from the leave-one-out-cross-validation. Overall, whatever the EB or carcass chemical or tissue components, R^2, MEF and CCC were improved (close to one) and MB absolute values reduced (close to 0) when serially slaughtered bulls were included (n = 66), compared to final slaughter bulls used only (n = 30). Conversely, residual CV (**rCV**) was most of the time slightly lower in the latter case.

Chemical composition

Body weight and HCW alone (equations A) provided a fair estimate of respectively EB and carcass water (rCV: 2.4–3.1%) as well as protein (rCV: 2.5–4.2%) masses, even if R^2 and MEF lower than 0.8 were recorded for the EB of final slaughter group. Conversely, estimates of EB and carcass lipid, mineral masses and energy content from only BW and HCW were less precise, with rCV ranging from 19.0-19.1, 9.4–10.6 and 7.5–9.1%, respectively. In the final slaughter group, relationships for lipids and minerals were even not significant, whereas for energy R^2, MEF and CCC dropped below 0.51, 0.50 and 0.70, respectively (Tables 2 and 3).

Adding 11th rib dissection weights to the predictive equations (set B) improved the estimation of water, lipid and energy masses. For serial slaughter group, when compared to BW or HCW alone, root mean square error of prediction (**RMSEP**) dropped of 1.3–1.4-fold and R^2 and MEF increased in the range +0.02 to +0.06. For final slaughter group, improvement of water and energy estimations were also recorded (RMSEP decrease of 1.2-fold and R^2 increase from +0.06 to +0.17), whereas for lipids, significant relationships could be established with rCV around 11–12%, but R^2 and MEF still lower than 0.70 and CCC, lower than 0.85. Conversely for proteins, improvement was slight, with RMSEP lowered by 1.1-fold and R^2 increased of less than +0.03. For minerals, the inclusion of rib variates did not improve estimative equations for serial slaughter group, but significant relationships were set for the final slaughter group, with rCV of 8.1–9.5% but R^2 of 0.16–0.17. Rib adipose tissue mass was significant in equations B, except for carcass mineral estimation in final slaughter group, where rib muscle and bone masses were involved. Besides, rib muscle mass was also significant in more than two-third of equations B, with the exception of EB lipids and energy and final slaughter EB and carcass proteins. Conversely, rib bone was rarely significant and only included for serial slaughter EB lipids and energy, and carcass minerals, and for final slaughter EB and carcass minerals.

More complex equations created by introducing either additional carcass classification (set C) or *postmortem* measurements (set D) allowed further increases in the precision of EB and carcass composition estimates. Especially for lipids and energy in the final slaughter group, further decreases in RMSEP (1.2–1.4-fold; i.e. rCV % decreased from 11–12% to 9–11% for lipids and from 6 to 5% for energy) and increases in R^2 and MEF (+0.11 to +0.30) were recorded in C and D equations, when compared to BW or HCW and rib dissection variate equations (set B). For water and minerals, improvements were smaller, with 1.1- to 1.2-fold decreases in RMSEP (rCV from 2.0–2.1% to 1.5–1.7% for water and from 8–10% to 7–9% for minerals) and increases in R^2 in the range +0.04 to +0.07 for water and +0.11 to +0.15 for minerals, whereas no relevant changes in precision was observed for proteins. In equations C, carcass fat score was included in every EB and carcass water, lipid and energy estimates, as well as for carcass proteins, whereas carcass conformation score was only included in mineral estimates and final slaughter EB proteins. In equations D, perirenal adipose tissue weight was always included, except for serial slaughter EB and carcass protein estimates. In addition, linear measurements of the thigh (e.g. length, thickness and compactness index) entered in seven of the 15 equations D, subcutaneous adipose tissue and *longissimus thoracis* muscle thicknesses between 11th and 12th rib in four and three equations, respectively, and lastly the canon bone weight in two equations.

Effect of crossbreed on regression intercept almost always was or tended to be significant ($P \leq 0.10$) for estimative equations of EB and carcass water, lipids, proteins and energy, with the exception of equations C (i.e. including carcass classification) for EB lipids and energy, carcass water of final slaughter group and carcass proteins of serial slaughter group (Tables 2 and 3). Compared to ×Limousin and ×Simmental, ×Angus crossbreed always led to higher intercept for lipid and energy estimative equations, and lower intercept for water and proteins. For EB and carcass mineral estimation, crossbreed effect was only significant for the final slaughter group (except equation C for EB), with lower intercept for ×Simmental crossbreed than for ×Angus and ×Limousin.

Carcass tissue composition

Only carcasses of the final slaughter group were physically dissected, and so have equations for adipose tissue, muscle and bone

Table 1
Mean ± standard deviation (SD) per crossbreed (×Angus, ×Limousin and ×Simmental), minimum and maximum of body anatomical and chemical component weights, 11th rib dissection variates and *postmortem* measurements of growing bulls slaughtered serially from 72 ± 10 kg to 514 ± 12 kg BW (n = 66: 3 × 22 of each crossbreed) or only at final slaughter BW of 514 kg (n = 30: 3 × 10 of each crossbreed, subpart of the 66).

Item		Serial slaughter					Final slaughter				
		Mean ± SD					Mean ± SD				
		×Angus	×Limousin	×Simmental	Min	Max	×Angus	×Limousin	×Simmental	Min	Max
Age (d)		260.0 ± 108.3	271.7 ± 109.2	256.8 ± 102.9	25	395	345.5 ± 29.3	355.9 ± 20.6	337.3 ± 26.6	302	395
BW (kg)		393.0 ± 154.2	389.8 ± 161.1	390.2 ± 154.5	58.4	534.0	513.4 ± 8.1	518.2 ± 8.7	509.9 ± 16.4	491.1	534.0
Digesta content (kg)		42.7 ± 16.0	38.0 ± 16.2	40.2 ± 15.5	1.5	61.3	53.2 ± 4.0	47.7 ± 3.7	49.5 ± 4.3	42.8	59.8
Empty BW (kg)		350.3 ± 139.2	351.8 ± 146.0	350.0 ± 140.6	55.8	484.6	460.2 ± 9.1	470.5 ± 7.2	460.4 ± 17.2	438.9	484.6
Hot carcass weight (kg)		218.6 ± 88.5	224.7 ± 95.5	217.2 ± 89.5	33.8	317.0	288.5 ± 7.9	303.2 ± 10.7	288.4 ± 14.1	272.8	317.0
Empty body chemical composition											
Masses (kg)											
	Water	217.4 ± 79.1	227.6 ± 89.5	230.2 ± 87.6	40.6	323.1	276.7 ± 6.8	299.5 ± 11.6	297.6 ± 11.8	267.8	323.1
	Lipids	58.3 ± 32.7	46.7 ± 25.9	41.8 ± 22.2	3.1	102.3	86.9 ± 8.4	67.4 ± 9.0	59.3 ± 9.1	44.9	102.3
	Proteins	62.4 ± 24.1	65.6 ± 27.6	66.0 ± 27.3	9.6	94.4	80.9 ± 2.6	88.5 ± 3.0	87.8 ± 4.2	77.4	94.4
	Minerals	12.4 ± 4.9	12.5 ± 5.1	12.2 ± 4.8	2.3	19.8	16.0 ± 1.5	16.6 ± 1.6	16.0 ± 1.1	13.7	19.8
	Energy (MJ)	3 722 ± 1 821	3 344 ± 1 629	3 164 ± 1 488	344	5 891	5 278 ± 322	4 675 ± 272	4 348 ± 402	3 727	5 891
Proportions (%)											
	Water	63.7 ± 4.4	66.0 ± 3.6	66.8 ± 3.0	57.9	72.8	60.1 ± 1.1	63.6 ± 1.7	64.6 ± 1.5	57.9	67.2
	Lipids	14.9 ± 5	11.9 ± 3.8	10.9 ± 3.0	5.1	22.1	18.9 ± 1.7	14.3 ± 2.1	12.9 ± 1.8	10.2	22.1
	Proteins	18.0 ± 0.7	18.6 ± 0.6	18.7 ± 0.6	16.7	19.6	17.6 ± 0.5	18.8 ± 0.4	19.1 ± 0.5	16.7	19.6
	Minerals	3.6 ± 0.3	3.6 ± 0.3	3.5 ± 0.3	2.8	4.2	3.5 ± 0.3	3.5 ± 0.3	3.5 ± 0.3	3.0	4.1
	Energy (MJ/kg)	10.0 ± 1.9	9.0 ± 1.5	8.6 ± 1.2	6.2	12.7	11.5 ± 0.6	9.9 ± 0.7	9.4 ± 0.7	8.5	12.7
Hot carcass chemical composition											
Masses (kg)											
	Water	137.6 ± 52.0	147.4 ± 60.2	144.2 ± 57.1	24.5	207.3	176.9 ± 5.6	196.0 ± 11.3	189.1 ± 9.9	168.2	207.3
	Lipids	32.6 ± 18.3	25.9 ± 14.3	22.9 ± 12.3	1.6	57.9	48.5 ± 5.6	37.6 ± 4.8	32.5 ± 5.4	24.0	57.9
	Proteins	39.4 ± 15.5	42.1 ± 18.1	41.0 ± 17.2	6.1	60.8	51.3 ± 1.7	57.2 ± 2.8	54.7 ± 3	48.5	60.8
	Minerals	8.9 ± 3.6	9.2 ± 3.9	8.7 ± 3.5	1.5	15.5	11.6 ± 1.2	12.4 ± 1.4	11.5 ± 0.9	9.9	15.5
	Energy (MJ)	2 203 ± 1 073	2 001 ± 966	1 866 ± 880	206	3 496	3 113 ± 216	2 806 ± 133	2 561 ± 266	2 192	3 496
Proportions (%)											
	Water	64.3 ± 3.7	66.7 ± 3.1	67.3 ± 2.5	59.2	72.6	61.3 ± 1.2	64.6 ± 1.7	65.6 ± 1.4	59.2	67.7
	Lipids	13.3 ± 4.3	10.4 ± 3.1	9.7 ± 2.5	4.8	19.9	16.8 ± 1.8	12.5 ± 2.0	11.3 ± 1.7	8.6	19.9
	Proteins	18.2 ± 0.7	18.7 ± 0.4	18.8 ± 0.4	17.0	20.0	17.8 ± 0.5	18.9 ± 0.4	19.0 ± 0.4	17.0	19.4
	Minerals	4.1 ± 0.3	4.1 ± 0.4	4.1 ± 0.4	3.4	5.1	4.0 ± 0.4	4.1 ± 0.5	4.0 ± 0.4	3.4	5.1
	Energy (MJ/kg)	9.5 ± 1.6	8.5 ± 1.2	8.2 ± 1.0	6.1	12.0	10.8 ± 0.6	9.3 ± 0.7	8.9 ± 0.7	7.9	12.0
Hot carcass anatomical composition											
Masses (kg)											
	Muscles		nd				176.2 ± 7.7	200.3 ± 15.1	190.1 ± 10.8	169.1	219.8
	Adipose tissues[1]		nd				50.0 ± 7.6	39.4 ± 5	34.4 ± 5.8	25.0	68.7
	Bones		nd				50.0 ± 3.2	50.6 ± 4.2	50.8 ± 3	44.2	58.0
	Remaining left[2]		nd				12.3 ± 3.7	12.9 ± 3.5	13.0 ± 2.7	8.2	20.2
Proportions (%)											
	Muscles		nd				61.1 ± 1.9	66.0 ± 3.0	65.9 ± 1.4	58.2	70.8
	Adipose tissues[1]		nd				17.3 ± 2.5	13.0 ± 1.9	11.9 ± 1.8	9.0	23.6
	Bones		nd				17.3 ± 1.1	16.7 ± 1.4	17.6 ± 0.9	14.6	19.1
	Remaining left[2]		nd				4.3 ± 1.3	4.3 ± 1.3	4.5 ± 1.0	2.7	7.2
11th rib anatomical composition											
Masses (g)											
	Total	1 044 ± 451	1 051 ± 447	990 ± 412	162	1 696	1 402 ± 159	1 367 ± 99	1 324 ± 102	1 105	1 696
	Muscles	640 ± 275	686 ± 292	642 ± 270	107	1 058	843 ± 125	893 ± 82	860 ± 76	661	1 058
	Adipose tissues[3]	223 ± 119	184 ± 97	163 ± 77	10	421	325 ± 50	242 ± 48	219 ± 33	179	421
	Bones	182 ± 70	182 ± 70	185 ± 70	43	291	233 ± 36	232 ± 29	245 ± 15	164	283
Proportions (%)											
	Muscles	61.8 ± 3.7	65.4 ± 3.1	64.9 ± 2.3	53.8	71.5	60.0 ± 3.8	65.4 ± 3.7	64.9 ± 1.8	53.8	70.7
	Adipose tissues[3]	19.8 ± 5.1	16.1 ± 4.5	15.8 ± 2.7	6.4	30.2	23.3 ± 3.7	17.7 ± 3.3	16.5 ± 1.9	13.6	30.2

(*continued on next page*)

Table 1 (*continued*)

Item	Serial slaughter					Final slaughter				
	Mean ± SD					Mean ± SD				
	×Angus	×Limousin	×Simmental	Min	Max	×Angus	×Limousin	×Simmental	Min	Max
Bones	18.4 ± 3.7	18.5 ± 3.8	19.4 ± 2.5	13.4	27.4	16.7 ± 1.9	16.9 ± 1.3	18.6 ± 1.1	13.5	20.4
Postmortem measurements										
Carcass classification (1–5 scale)[4]										
Fat score	2.9 ± 1.2	2.4 ± 0.9	2.1 ± 0.8	1.0	4.0	3.8 ± 0.4	2.9 ± 0.6	2.5 ± 0.5	2.0	4.0
Conformation score	3.8 ± 0.7	4.0 ± 0.8	4.0 ± 0.8	2.5	5.0	4.1 ± 0.5	4.6 ± 0.5	4.6 ± 0.5	3.5	5.0
Thigh thickness (cm)	23.7 ± 4.9	24.3 ± 5.2	24.1 ± 4.8	11.8	29.1	26.6 ± 0.8	28.1 ± 0.7	27.3 ± 1	25.5	29.1
Hook-symphisis length (cm)	71.5 ± 8.3	74.7 ± 9.4	71.9 ± 8.4	50.5	84.0	77.1 ± 2.5	80.3 ± 2.1	77.6 ± 1.8	71.0	83.3
Thigh compactness index (no unit)[5]	0.33 ± 0.04	0.32 ± 0.05	0.33 ± 0.04	0.20	0.42	0.35 ± 0.02	0.35 ± 0.01	0.35 ± 0.01	0.32	0.38
Perirenal adipose tissue weight (kg)	6.2 ± 3.7	5.7 ± 3.6	4.8 ± 3.1	0.3	13.2	9.2 ± 1.1	8.6 ± 1.8	7.1 ± 2.4	4.3	13.2
Four canon bones weight (kg)	2.4 ± 0.6	2.5 ± 0.7	2.5 ± 0.6	1.0	3.3	2.9 ± 0.3	3.1 ± 0.2	2.9 ± 0.2	2.5	3.3
Subcutaneous adipose tissue thickness (mm)[6]	3.8 ± 2.2	2.2 ± 1.6	2.5 ± 1.3	0.1	8.0	5.0 ± 1.8	2.8 ± 1.6	3.2 ± 1	1.8	8.0
Longissimus thoracis muscle thickness (mm)[6]	71 ± 13	74 ± 17	72 ± 15	35	98	77 ± 7	85 ± 6	83 ± 7	64	98

nd: not determined.

[1] Sum of dissected subcutaneous, intermuscular and internal (i.e. covering the thoracic and abdominal cavity) adipose tissues.

[2] Mainly ligaments and tendons.

[3] Sum of dissected subcutaneous and intermuscular adipose tissues.

[4] According to the Swiss CH-TAX carcass classification system (Order 916.341.22 of Swiss federal laws, 1999, last update 2003). For conformation score, the following numerical conversion was performed: C = 5, H = 4, T+ = 3.5, T = 3, T− = 2.5, A = 2 and X = 1.

[5] Ratio of thigh thickness to hook-symphisis length.

[6] Measured between the 11th and 12th ribs.

mass estimations reported in Table 3. Hot carcass weight alone (equations A) provided a good estimate of carcass muscle mass (R^2 of 0.80 and rCV of 3.51%), whereas no relationship can be fit for adipose tissues and bones ($P > 0.10$). Adding 11th rib dissection weights to the predictive equations (set B) improved the estimation of carcass muscle mass, with a drop in RMSEP of 1.2-fold, and an increase in R^2 of +0.06. Besides, significant relationships were found for adipose tissues (R^2 of 0.65 and rCV of 12.7%) and bones (R^2 of 0.12 and rCV of 6.5%). Rib adipose tissue and bone masses were always included, with additionally rib muscle mass for carcass muscle estimate. With further inclusion of carcass classification (set C) or *postmortem* measurement (set D) variates, slight improvements were achieved, i.e. decrease in RMSEP of 1.1, 1.2 and 1.2-fold and increase in R^2 of +0.02, +0.11 and +0.27 for muscles, adipose tissues and bones, respectively. Carcass conformation score or perirenal adipose tissue weight were included in every C and D equations, respectively. Effect of crossbreed on regression intercept was or tended to be significant ($P \leq 0.10$), except for carcass bone estimative equations C and D. Elsewhere, ×Angus crossbreed led to lower intercept for muscle and higher intercept for adipose tissue estimates, compared to ×Limousin and ×Simmental.

Estimation of empty body and carcass component proportions

The most precise simple and multiple linear regression equations for the estimation of EB and carcass water, lipid, protein, mineral and energy proportions are reported in Figs. 2 and 3 and Tables S1 and S2. Overall, when compared to component masses, the estimative equations for proportions had lower R^2, MEF and CCC, but comparable rCV. Exceptions concerned EB and carcass lipids, minerals and energy as well as carcass adipose tissues and bones for the final slaughter group, for which R^2, MEF and CCC were slightly higher for proportions than for masses estimations. The HCW alone (equations A) failed to estimate the component proportions for the final slaughter group and only provided significant single linear relationships for the serial slaughter group EB and carcass water, lipids and energy, as well as carcass muscles (rCV: 2.1–15.5%). Besides, when 11th rib adipose tissue proportion was used as a single predictive variate, similar precision (i.e. R^2 and RMSEP) was recorded than with HCW alone for carcass water, lipid and energy proportions in the serial slaughter group. Additionally, 11th rib muscle and adipose tissue proportions also provided good estimates of carcass muscle (rCV of 2.3%) and adipose tissue (rCV of 11.1%) proportions, respectively (Figs. 2 and 3).

Precision of estimative equations was increased when combining BW or HCW and 11th rib dissection variates into multiple linear regressions (set B). In such cases, rCV of 1.5–1.9% for water, 10.2–11.4% for lipid, 2.3–2.9% for protein, 8.3–9.7% for mineral and 5.3–5.9% for energy proportions in EB or carcass of both slaughter groups were recorded, as well as rCV of 2.5%, 11.8 and 6.3% for muscle, adipose tissue and bone proportions, respectively, in carcass of the final slaughter group. In most of the B equations, rib adipose tissue proportion was included, except for EB and carcass mineral and carcass bone proportions with rib bone proportion, and for carcass muscles with rib muscle proportion included. Further improvements of equation precision were achieved when carcass fat score was included with BW or HCW and 11th rib dissection variates (set C), rCV decreasing on average by 1.3-fold when compared to B equations. Conversely, improvements were limited when *postmortem* measurements were added instead of carcass classification (set D, rCV decreases on average by 1.2-fold when compared to B equations, Tables S1 and S2).

Effect of crossbreed on intercept of equations always was or tended to be significant ($P \leq 0.10$), except for EB and carcass protein and mineral proportions in the serial slaughter group, for all

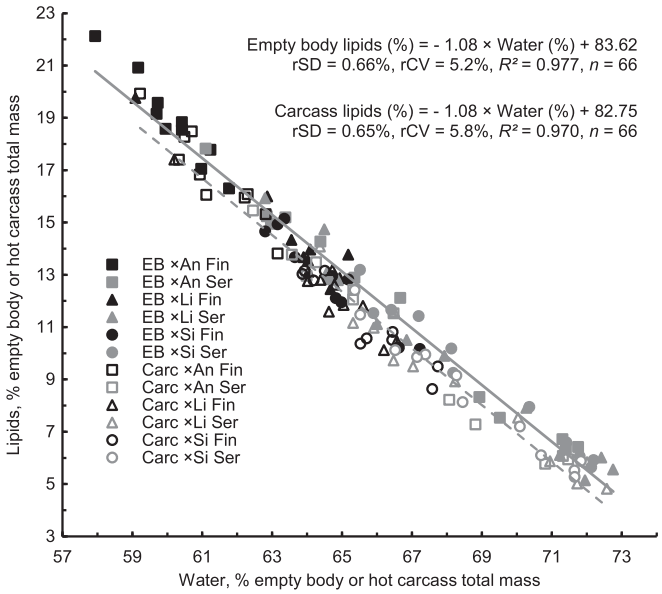

Fig. 1. Relationship between crossbred growing bull empty body or hot carcass water and lipid proportions. EB: empty body, Carc: hot carcass, ×An: crossbreed Angus, ×Li: crossbreed Limousin, ×Si: crossbreed Simmental, Fin: final slaughter (n = 30), Ser: serial slaughter (additional n = 36). Full grey line: linear regression for empty body. Dotted grey line: linear regression for hot carcass (final plus serial slaughter).

EB mineral and carcass bone equations and for equations C for water, lipids and energy in the final slaughter group. As for mass estimations, compared to ×Limousin and ×Simmental, the ×Angus crossbreed constantly led to higher intercept for lipid, energy and adipose tissue estimative equations, and lower intercept for water, proteins and muscles. For carcass mineral estimation in the final slaughter group, the intercept was lower for ×Simmental crossbreed than for ×Limousin.

Author's point of view

Body composition measured after slaughter

The straight linear and negative relationship between water and lipid proportions (rCV $\leq$ 5.8%, $R^2 \geq 0.97$) and the fairly constant composition of the lipid-free EB and carcass were expected and are well-established in animals (Speakman, 2001). This highlighted the repeatability and reproducibility of both grinding and homogenisation procedures as well as further chemical analyses. Similar straight relationships between EB water and lipid proportions were recorded previously in beef cows (R^2 = 0.98, Fiems et al., 2005), lactating cows and growing calves (rCV = 3.5% and R^2 = 0.97, Xavier et al., 2022), dairy goats (5.9% and 0.98, Lerch et al., 2021) and dairy ewes (3.2% and 0.98, Bocquier et al., 1999). Also, the lipid-free EB composition in the present study was remarkably close to those observed by others (71.1–74.4% water; 19.2–22.6% proteins and 4.1–5.8% minerals, Bocquier et al., 1999; Fiems et al., 2005; Lerch et al., 2021; Xavier et al., 2022). The slight variations among and between studies are presumably linked to the slight decrease in the water proportion of the lipid-free EB, concomitant with an increase in EB lipid proportion, as discussed by Bocquier et al. (1999).

Estimation of body composition from 11th rib dissection

As a single predictive variate, the 11th rib adipose tissue proportion provided a good estimate of carcass water, lipid, energy and adipose tissue proportions, as well as 11th rib muscle proportion for carcass muscle proportion (rCV from 2.2% for muscles to 15.7% for lipids and R^2 from 0.76 for energy to 0.80 for muscles). Similarly, De Campeneere et al. (1999) and Fiems et al. (2005) using the 8th rib dissection of Belgian Blue bulls and cows, and Robelin et al. (1975) using the 11th rib dissection of bulls from several breeds, found similar precision relationships between rib adipose tissue proportion and EB and carcass water, lipid and energy proportions ($R^2 \geq 0.76$ and rCV $\leq$ 2.1, 10.7 and 6.2% for water, lipid and energy, respectively). Regarding carcass tissue composition, Geay and Béranger (1969), also using 11th rib dissection in bulls and steers, obtained similar precision for adipose tissue (R^2 of 0.90 and rCV of 14.0%) and muscle (0.89 and 2.9%) estimative equations. Conversely, single rib dissection variates failed to estimate precisely EB or carcass protein, mineral and bone proportions ($R^2 \leq 0.24$), as in previous studies ($R^2 \leq 0.54$, Geay and Béranger, 1969; Robelin et al., 1975; De Campeneere et al., 1999; Fiems et al., 2005). Overall, when BW or HCW was added to 11th rib dissection variates for EB or carcass composition estimations (equations B), relevant improvements in estimative equations were achieved compared to either BW or HCW alone (equations A), or rib dissection variate alone. For most of the chemical and tissue component masses and proportions, in the final slaughter group, R^2 ranged from 0.60 to 0.89 and rCV from 1.9 to 12.7%. This confirmed earlier observations in bulls (Robelin and Geay, 1975b and 1976; De Campeneere et al., 1999) beef cows (Fiems et al., 2005) and lactating cows and calves (Xavier et al., 2022) with remarkably close rCV (1.7–11.6%). Exceptions were minerals and bones which remained difficult to estimate well in line with previously published results (Robelin and Geay, 1975b and 1976; Fiems et al., 2005).

More complex estimative equations created by introducing additional carcass classification variates (equations C) or *postmortem* measurements (equations D) resulted in limited improvements in precision. The most improved equations were the ones involving a carcass classification trait (most of the time, the fat score) in addition to BW or HCW and 11th rib dissection variates. In such cases, R^2 ranged from 0.70 to 0.93 and rCV from 1.4 to 10.5%, with the exception of minerals and bones (R^2 from 0.26 to 0.47 and rCV from 5.0 to 9.1%). Similarly, Fiems et al. (2005) improved the precision of estimative equations for EB lipid mass and energy content by including carcass fat score from the EUROP classification scheme together with BW and 8th rib adipose tissue mass (R^2 increased of +0.02 and +0.01 and RMSEP decreased of 1.3 and 1.2-fold for lipids and energy, respectively, when compared to BW and rib adipose tissues only). Nonetheless, differences in carcass grading schemes used worldwide, sometimes with subjectivity in fat and conformation scoring when performed manually (i.e. sensitive to operator effect, Monteils et al., 2017), may lead to error and bias when using estimative equations including them. The use instead of *postmortem* linear and weight measurements into equations may counteract such limitations, even if precision improvement is slightly lower than with carcass classification in the present study. Similarly, Fiems et al. (2005) in beef cows, Geay and Béranger (1969) and Robelin and Geay (1975b and 1976) in bulls noticed a limited increased R^2 of +0.01 to +0.02 and a decreased rCV by 1.1 to 1.3-fold, when adding linear measurements (chest grid, perirenal adipose tissue weight or thigh compactness index) to HCW and 8th or 11th rib dissection variates.

Most of the estimative equations calibrated in the present study were significantly improved when crossbreed effect on the intercept was included. This was particularly the case for ×Angus crossbreed, which resulted to higher intercept for EB and carcass lipid, energy and adipose tissue masses and proportions, and the reverse for water, proteins and muscles, when compared to ×Limousin and ×Simmental. Previously, higher intercepts in estimative equations

Table 2
Most precise estimation equations of empty body chemical component masses of crossbred growing bulls measured after slaughter with independent variates derived from 11th rib dissection, carcass classification and *postmortem* anatomical measurements, associated with BW.

Component (kg unless stated)	Group		Statistics								
			Calibration			Leave-one-out-cross-validation[2]					
		Equation[1]	RMSE	rCV (%)	R^2	RMSEP	rCV (%)	R^2	MB	MEF	CCC
Water											
	Serial slaughter (n = 66)										
	A	0.544 × BW + (3.481, 15.432, 17.681)	6.725	3.0	0.994	6.942	3.1	0.993	−0.01	0.993	0.997
	B	0.581 × BW − 0.117 × rAT + 0.018 × rM + (3.727, 10.415, 11.005)	4.685	2.1	0.997	4.944	2.2	0.997	−0.04	0.997	0.998
	C	0.592 × BW − 0.091 × rAT + 0.015 × rM − 4.067 × CarcFS + (6.933, 12.772, 12.676)	4.418	2.0	0.998	4.666	2.1	0.997	−0.05	0.997	0.998
	D	0.578 × BW − 0.094 × rAT + 0.015 × rM − 0.925 × PRAT + *0.156* × *LT_thick* + (−3.608, 3.119, 3.530)	4.419	2.0	0.998	4.740	2.1	0.997	−0.03	0.997	0.998
	Final slaughter (n = 30)										
	A	0.708 × BW + (−86.924, −67.524, −63.543)	6.319	2.2	0.829	7.023	2.4	0.759	−0.09	0.757	0.868
	B	0.580 × BW − 0.085 × rAT + *0.021* × *rM* + (−11.876, 0.009, 1.696)	4.947	1.7	0.904	5.799	2.0	0.837	−0.18	0.834	0.914
	C	0.679 × BW − 0.051 × rAT − 6.542 × CarcFS + (−30.219, −20.847, −20.908)	4.257	1.5	0.929	4.812	1.7	0.887	−0.03	0.886	0.941
	D	0.472 × BW + 0.074 × rB − 1.561 × AT_thick − 1.926 × PRAT + 9.651 × CB + (14.806, 28.728, 29.241)	3.695	1.3	0.951	4.292	1.5	0.910	−0.13	0.909	0.954
Lipids											
	Serial slaughter										
	A	0.165 × BW + (−6.440, −17.475, −22.413)	8.981	18.4	0.900	9.289	19.0	0.886	0.05	0.886	0.940
	B	0.095 × BW + 0.164 × rAT − *0.060* × *rB* + (−4.797, −9.637, −10.920)	6.229	12.7	0.953	6.632	13.6	0.942	0.04	0.942	0.970
	C	0.052 × BW + 0.109 × rAT + 9.569 × CarcFS + -15.236	5.481	11.2	0.963	5.739	11.7	0.957	0.04	0.957	0.978
	D	0.100 × BW + 0.096 × rAT − 0.364 × Sh-Sy_length + 2.265 × PRAT − 0.196 × LT_thick + (23.587, 19.029, 16.697)	5.146	10.5	0.969	6.018	12.3	0.953	0.17	0.952	0.976
	Final slaughter										
	B	0.123 × rAT + (46.890, 37.627, 32.344)	7.102	10.0	0.787	7.970	11.2	0.695	0.06	0.690	0.830
	C	0.094 × rAT + 11.629 × CarcFS + 10.975	5.535	7.8	0.866	6.207	8.7	0.814	−0.08	0.812	0.901
	D	0.076 × rAT + 223.385 × Th_comp + 1.631 × PRAT + (−30.138, −43.384, −47.586)	5.705	8.0	0.873	6.711	9.4	0.785	0.07	0.780	0.884
Proteins											
	Serial slaughter										
	A	0.168 × BW + (−3.504, 0.211, 0.521)	2.627	4.1	0.990	2.712	4.2	0.989	0.01	0.989	0.994
	B	0.172 × BW − 0.031 × rAT + 0.008 × rM + (−3.319, −1.162, −1.145)	2.291	3.5	0.993	2.402	3.7	0.991	0.00	0.991	0.996
	D	0.183 × BW − 0.031 × rAT − 25.634 × Th_comp + 0.088 × LT_thick + (−0.588, 1.526, 1.619)	2.269	3.5	0.993	2.395	3.7	0.991	0.00	0.991	0.996
	Final slaughter										
	A	0.232 × BW + (−38.289, −31.762, −30.546)	1.983	2.3	0.844	2.111	2.5	0.797	0.00	0.797	0.890
	B	0.220 × BW − 0.018 × rAT + (−26.274, −21.229, −20.533)	1.842	2.1	0.871	2.001	2.3	0.819	0.03	0.817	0.903
	C	0.249 × BW − 0.018 × rAT − 1.502 × CarcCS + (−35.179, −29.470, −28.521)	1.727	2.0	0.891	1.908	2.2	0.835	0.00	0.834	0.913
Minerals											
	Serial slaughter										
	A	0.030 × BW + *0.495*[a]	1.156	9.3	0.944	1.166	9.4	0.941	0.00	0.941	0.969
	C	0.038 × BW − 0.006 × rAT − 1.087 × CarcCS + 2.888	1.054	8.5	0.955	1.081	8.7	0.949	−0.01	0.949	0.974
	Final slaughter										
	B	− 0.016 × rAT − 0.006 × rM + 0.031 × rB + (19.383, 19.009, 17.393)	1.223	7.6	0.383	1.313	8.1	0.160	0.00	0.112	0.358
	C	0.037 × BW − 0.010 × rAT − 1.811 × CarcCS + *7.740*[a]	1.111	6.9	0.449	1.176	7.3	0.306	−0.01	0.288	0.517
Energy (MJ)	Serial slaughter										
	A	10.34 × BW + (−341.13, −685.48, −870.37)	326.08	9.6	0.962	337.67	9.9	0.957	2.11	0.957	0.978
	B	8.14 × BW + 5.52 × rAT − *2.34* × *rB* + (−280.15, −416.2, −477.39)	244.86	7.2	0.979	261.06	7.7	0.974	2.12	0.974	0.987
	C	6.58 × BW + 3.26 × rAT + 356.93 × CarcFS − 652.16	212.95	6.2	0.984	222.95	6.5	0.981	1.54	0.981	0.991
	D	7.62 × BW + 2.46 × rAT − *25.93* × *Th_thick* + 104.94 × PRAT + (148.41, −42.75, −88.58)	205.93	6.0	0.986	217.86	6.4	0.982	1.06	0.982	0.991

Table 2 (*continued*)

Component (kg unless stated)			Statistics								
Group			Calibration			Leave-one-out-cross-validation[2]					
	Equation[1]		RMSE	rCV (%)	R^2	RMSEP	rCV (%)	R^2	MB	MEF	CCC
Final slaughter											
	A	*9.28 × BW* + (512.81, −134.31, −384.68)	324.36	6.8	0.635	356.30	7.5	0.503	4.15	0.492	0.694
	B	12.05 × BW + 4.36 × rAT + (*−2 325.98, −2 623.14, −2 750.44)*	265.33	5.6	0.765	306.80	6.4	0.634	6.67	0.624	0.792
	C	11.04 × BW + 3.03 × rAT + 398.21 × CarcFS − *2917.18*	201.01	4.2	0.860	225.73	4.7	0.798	−4.73	0.796	0.892
	D	10.78 × BW + 2.53 × rAT − *0.84* × *rM* + 9615.90 × Th_comp + 57.80 × PRAT + (−4 225.93, −4 638.42, −4 771.67)	197.11	4.1	0.886	241.04	5.1	0.775	7.21	0.768	0.879

[1] A–D correspond to four regression equations of increasing complexity involving single (A) or multiple (B–D) predictive variates. A: preslaughter BW (BW, kg); B: BW and 11th rib dissection (rib adipose tissue, rAT; muscle, rM; and bone, rB masses, g); C: BW, rib dissection and carcass classification (fat score CarcFS; conformation score, CarcCS, 1–5 scale, for conformation score, the following numerical conversion was performed: C = 5, H = 4, T+ = 3.5, T = 3, T− = 2.5, A = 2 and X = 1); D: BW, rib dissection and *postmortem* anatomical measurements (perirenal adipose tissue weight, PRAT, kg; four canon bones weight, CB, kg; thigh thickness, Th_thick, cm; shunk-symphisis length, Sh-Sy_length, cm; thigh compactness index, Th_comp; subcutaneous adipose tissue thickness between 11th and 12th ribs, AT_thick, mm; *Longissimus thoracis* muscle thickness between 11th and 12th ribs, LT_thick, mm). Only significant models that improve the prediction compared to a simplest one are presented. All variates retained in the regression equations presented are significant ($P \leq 0.05$), except the ones in italics that tended to be significant ($P \leq 0.10$). When placed in brackets, the intercept was different ($P \leq 0.05$ or $P \leq 0.10$ when italics) according to the crossbreed, and is further presented in the following order: ×Angus, ×Limousin, ×Simmental.

[2] RMSEP: root mean square error of prediction, MB: Mean bias, MEF: modelling efficiency statistic, CCC: Concordance correlation coefficient.

[a] When italics with an *a* upperscript, the intercept is not different from 0 ($P > 0.10$).

Table 3

Most precise estimation equations of carcass chemical and anatomical component masses of crossbred growing bulls measured after slaughter with independent variates derived from 11th rib dissection, carcass classification and *postmortem* anatomical measurements, associated with hot carcass weight.

Component (kg unless stated)			Statistics								
Group			Calibration			Leave-one-out-cross-validation[2]					
	Equation[1]		RMSE	rCV (%)	R^2	RMSEP	rCV (%)	R^2	MB	MEF	CCC
Water											
Serial slaughter (n = 66)											
	A	0.618 × HCW + (2.489, 8.551, 10.006)	4.066	2.8	0.995	4.200	2.9	0.994	−0.02	0.994	0.997
	B	0.627 × HCW − 0.064 × rAT + 0.018 × rM + (3.177, 5.861, 6.840)	2.943	2.1	0.997	3.118	2.2	0.997	−0.02	0.997	0.998
	C	0.643 × HCW − 0.042 × rAT + 0.016 × rM − 3.263 × CarcFS + (5.892, 7.811, 8.356)	2.648	1.9	0.998	2.820	2.0	0.997	−0.02	0.997	0.999
	D	0.614 × HCW − 0.043 × rAT + 0.019 × rM + 0.369 × Th_thick − 0.868 × PRAT + (−2.741, 0.174, 0.847)	2.648	1.9	0.998	2.819	2.0	0.997	−0.03	0.997	0.999
Final slaughter (n = 30)											
	A	0.733 × HCW + (−34.457, −26.078, −22.112)	4.296	2.3	0.885	4.937	2.6	0.827	−0.12	0.825	0.908
	B	0.591 × HCW − 0.057 × rAT + 0.02 × rM + (8.019, 12.728, 13.954)	3.334	1.8	0.936	3.978	2.1	0.888	−0.06	0.886	0.942
	C	0.622 × HCW − 0.045 × rAT + 0.016 × rM − 4.771 × CarcFS + *17.300*[a]	2.822	1.5	0.952	3.262	1.7	0.925	0.11	0.923	0.962
	D	0.507 × HCW + 0.019 × rM − 1.32 × PRAT − 1.097 × AT_thick + (32.488, 39.870, 39.630)	3.150	1.7	0.945	3.688	2.0	0.903	−0.17	0.902	0.950
Lipids											
Serial slaughter											
	A	0.157 × HCW + (−1.774, −9.358, −11.165)	5.029	18.5	0.899	5.194	19.1	0.886	0.02	0.886	0.940
	B	0.131 × HCW + 0.083 × rAT − 0.019 × rM + (−2.623, −5.992, −7.088)	3.575	13.2	0.951	3.806	14.0	0.939	0.03	0.939	0.969
	C	0.110 × HCW + 0.053 × rAT − 0.015 × rM + 4.445 × CarcFS + (−6.321, −8.649, −9.154)	3.110	11.5	0.963	3.335	12.3	0.953	0.03	0.953	0.976
	D	0.120 × HCW + 0.061 × rAT − 0.018 × rM + 0.961 × PRAT + (−1.251, −4.933, −5.731)	3.387	12.5	0.957	3.583	13.2	0.946	0.03	0.946	0.972
Final slaughter											
	B	0.234 × HCW + 0.077 × rAT − 0.02 × rM + (−27.221, −34.143, −34.701)	4.089	10.3	0.808	4.859	12.3	0.673	0.02	0.662	0.818
	C	0.196 × HCW + 0.049 × rAT − 0.015 × rM + 5.433 × CarcFS + *(−32.020, −36.119, −35.548)*	3.204	8.1	0.887	3.954	10.0	0.782	−0.10	0.776	0.883
	D	0.342 × HCW − 0.019 × rM + 1.419 × AT_thick + 1.762 × PRAT + (−57.857, −68.473, −67.155)	3.881	9.8	0.834	4.510	11.4	0.715	0.17	0.708	0.843

(*continued on next page*)

Table 3 (*continued*)

Component (kg unless stated)			Statistics								
Group			Calibration			Leave-one-out-cross-validation[2]					
		Equation[1]	RMSE	rCV (%)	R^2	RMSEP	rCV (%)	R^2	MB	MEF	CCC
Proteins											
Serial slaughter											
	A	0.185 × HCW + (−1.122, 0.447, 0.735)	1.244	3.0	0.995	1.283	3.1	0.994	0.00	0.994	0.997
	B	0.191 × HCW − 0.016 × rAT + *0.003* × *rM* + (−0.963, −0.188, −0.040)	1.059	2.6	0.996	1.116	2.7	0.995	0.00	0.995	0.998
	C	0.196 × HCW − 0.012 × rAT + *0.003* × *rM* − 0.999 × CarcFS + *0.156*[a]	1.024	2.5	0.996	1.079	2.6	0.996	0.00	0.996	0.998
	D	0.202 × HCW − 0.018 × rAT + 0.004 × rM − 1.474 × CB + (0.451, 1.196, 1.393)	1.034	2.5	0.997	1.097	2.7	0.996	0.00	0.996	0.998
Final slaughter											
	A	0.201 × HCW + (−6.764, −3.807, −3.318)	1.280	2.4	0.880	1.364	2.5	0.843	0.00	0.843	0.917
	B	0.187 × HCW − 0.011 × rAT + (1.099, 3.336, 3.351)	1.211	2.2	0.897	1.330	2.4	0.851	0.02	0.851	0.921
	C	0.198 × HCW − 0.981 × CarcFS + (−2.180, −0.063, −0.011)	1.198	2.2	0.899	1.304	2.4	0.857	0.03	0.857	0.925
Minerals											
Serial slaughter											
	A	0.039 × HCW + *0.340*[a]	0.945	10.5	0.934	0.955	10.6	0.930	0.00	0.930	0.964
	B	0.043 × HCW − *0.003* × *rM* + *0.008* × *rB* + *0.149*[a]	0.931	10.4	0.938	0.966	10.8	0.929	−0.01	0.929	0.963
	C	0.053 × HCW − *0.004* × *rAT* − *0.003* × *rM* + *0.008* × *rB* − 1.076 × CarcCS + 2.628	0.818	9.1	0.954	0.865	9.6	0.943	−0.01	0.943	0.971
Final slaughter											
	B	− 0.012 × rAT − 0.005 × rM + 0.024 × rB + (14.493, 14.58, 12.895)	1.039	8.8	0.395	1.128	9.5	0.165	−0.01	0.109	0.369
	C	− 0.010 × rAT + *0.012* × *rB* − 1.152 × CarcCS + (16.957, 17.485, 16.198)	0.949	8.0	0.495	1.073	9.1	0.263	0.02	0.193	0.497
	D	− *0.036* × *HCW* − 0.006 × rM + 0.029 × rB − 0.456 × AT_thick − 0.262 × PRAT + (25.154, 25.629, 23.413)	0.953	8.0	0.533	1.055	8.9	0.273	0.00	0.221	0.502
Energy (MJ)											
Serial slaughter											
	A	10.52 × HCW + (−97.04, −362.53, −418.75)	178.92	8.8	0.968	184.752	9.1	0.963	0.71	0.963	0.981
	B	9.71 × HCW + 2.77 × rAT − 0.64 × rM + (−125.7, −249.01, −281.71)	133.88	6.6	0.982	142.445	7.0	0.978	1.19	0.978	0.989
	C	8.91 × HCW + 1.68 × rAT − 0.51 × rM + 164.96 × CarcFS + *(−262.96, −347.61, −358.4)*	116.81	5.8	0.987	125.250	6.2	0.983	1.09	0.983	0.992
	D	10.25 × HCW + 1.92 × rAT − 0.68 × rM − 15.18 × Th_thick + 34.76 × PRAT + (116.5, −15.98, −36.37)	123.96	6.1	0.985	132.804	6.6	0.981	2.31	0.981	0.990
Final slaughter											
	A	8.60 × HCW + (630.31, 197.04, 80.17)	192.69	6.8	0.648	217.373	7.7	0.499	4.65	0.484	0.694
	B	14.677 × HCW + 2.69 × rAT − 0.76 × rM + (−1 359.88, −1 619.28, −1 609.34)	150.46	5.3	0.802	176.569	6.2	0.670	2.12	0.659	0.816
	C	13.31 × HCW + 1.67 × rAT − 0.57 × rM + 195.87 × CarcFS + *(−1 532.88, −1 690.51, −1 639.87)*	119.53	4.2	0.880	143.919	5.1	0.778	−1.80	0.774	0.881
	D	15.95 × HCW + 1.68 × rAT − 0.76 × rM + 42.34 × PRAT + (−1 789.60, −2 123.20, −2 054.80)	140.35	5.0	0.835	160.063	5.7	0.726	3.81	0.720	0.849
Muscles											
Final slaughter											
	A	0.886 × HCW + (−79.399, −68.318, −65.362)	6.074	3.2	0.853	6.643	3.5	0.799	−0.08	0.8	0.892
	B	0.686 × HCW − 0.050 × rAT + 0.045 × rM − 0.095 × rB + (−21.135, −13.717, −12.110)	4.657	2.5	0.924	5.602	3.0	0.857	−0.07	0.9	0.925
	D	0.659 × HCW + 0.049 × rM − 0.125 × rB − 1.354 × PRAT + (−13.543, −2.764, −1.872)	4.499	2.4	0.929	5.313	2.8	0.872	−0.16	0.9	0.933
Adipose tissues											
Final slaughter											
	B	0.280 × HCW + 0.105 × rAT − 0.091 × rB + *(−43.624, −49.707, −46.904)*	4.418	10.7	0.797	5.254	12.7	0.646	0.16	0.6	0.796
	C	0.175 × HCW + 0.062 × rAT − 0.020 × rM + 4.290 × CarcCS + 4.349 × CarcFS + *(−37.647, −42.857, −42.766)*	3.442	8.3	0.887	4.351	10.5	0.757	0.04	0.8	0.867
	D	0.374 × HCW + 0.056 × rAT − 0.024 × rM + 1.528 × PRAT + (−70.473, −79.594, −76.257)	4.141	10.0	0.829	4.675	11.3	0.719	0.13	0.7	0.843
Bones											
Final slaughter											
	B	− 0.044 × rAT + 0.042 × rB + *(54.508, 51.537, 50.185)*	3.010	6.0	0.336	3.266	6.5	0.117	0.01	0.062	0.296
	C	0.132 × HCW − 0.027 × rAT + *0.027* × *rB* − 4.248 × CarcCS + 31.326	2.483	4.9	0.548	2.705	5.4	0.382	0.06	0.357	0.599
	D	0.102 × HCW − *0.013* × *rM* + 0.057 × rB − 0.210 × LT_thick − 0.774 × PRAT + 5.702 × CB + 24.652	2.497	4.9	0.580	2.735	5.4	0.370	0.05	0.342	0.589

[1] A–D correspond to four regression equations of increasing complexity involving single (A) or multiple (B–D) predictive variates. A: Hot carcass weight (HCW, kg); B: HCW and 11th rib dissection (rib adipose tissue, rAT; muscle, rM; and bone, rB masses, g); C: HCW, rib dissection and carcass classification (fat score CarcFS; conformation score, CarcCS, 1–5 scale, for conformation score, the following numerical conversion was performed: C = 5, H = 4, T+ = 3.5, T = 3, T− = 2.5, A = 2 and X = 1); D: HCW, rib dissection and *postmortem* anatomical measurements (perirenal adipose tissue weight, PRAT, kg; four canon bones weight, CB, kg; thigh thickness, Th_thick, cm; subcutaneous adipose tissue thickness between 11th and 12th ribs, AT_thick, mm; *Longissimus thoracis* muscle thickness between 11th and 12th ribs, LT_thick, mm). Only significant models that improve the prediction compared to a simplest one are presented. All variates retained in the regression equations presented are significant ($P \leq 0.05$), except the ones in italics that tended to be significant ($P \leq 0.10$). When placed in brackets, the intercept was different ($P \leq 0.05$ or $P \leq 0.10$ when italics) according to the crossbreed, and is further presented in the following order: ×Angus, ×Limousin, ×Simmental.

[2] RMSEP: root mean square error of prediction, MB: Mean bias, MEF: modeling efficiency statistic, CCC: Concordance correlation coefficient.

[a] When italics with an *a* upperscript, the intercept is not different from 0 ($P > 0.10$).

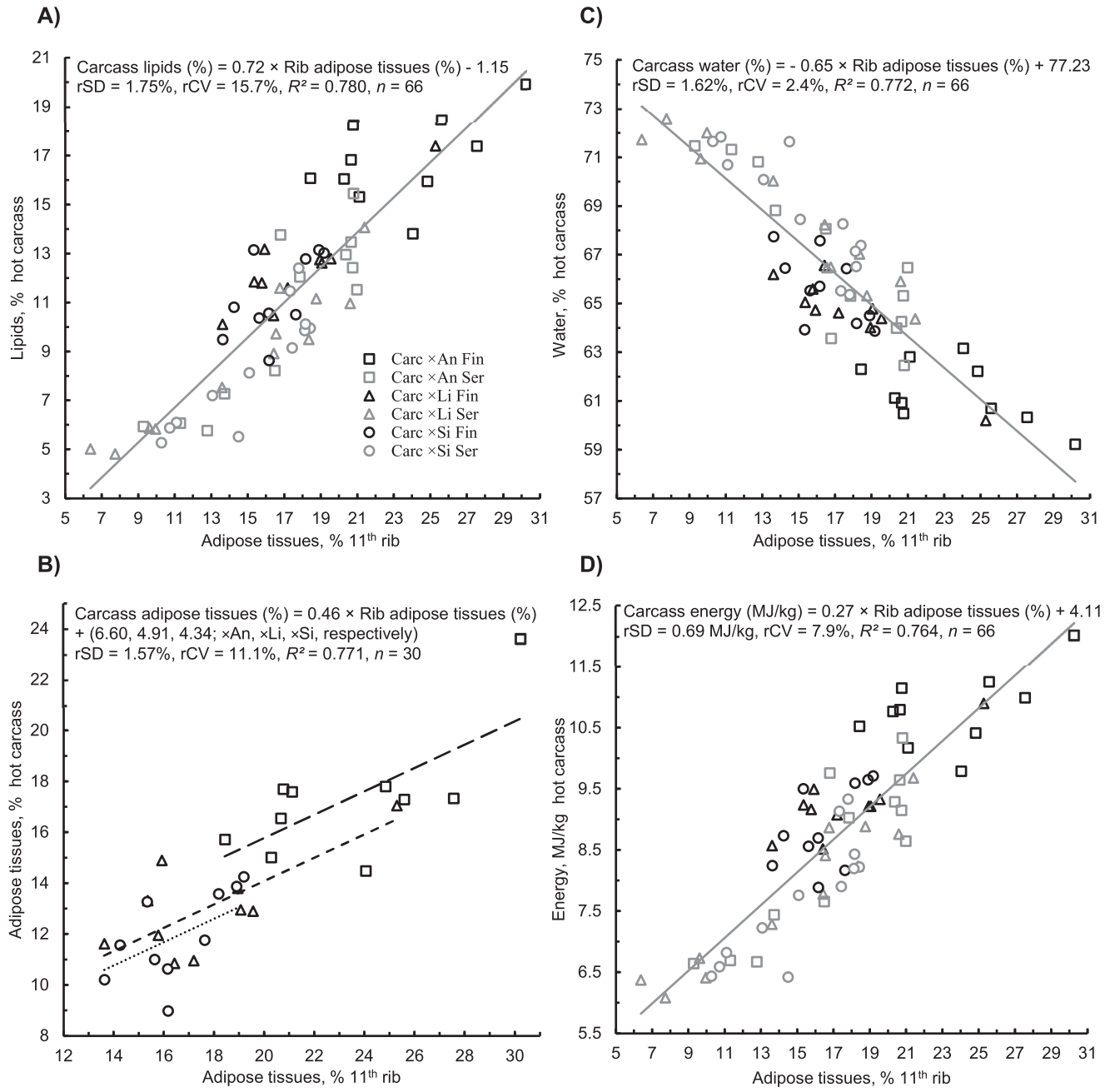

Fig. 2. Relationship between adipose tissue proportion in the 11th rib and lipid (A), adipose tissue (B), water (C) and energy (D) proportions in the hot carcass from crossbred growing bull. Carc: hot carcass, ×An: crossbreed Angus, ×Li: crossbreed Limousin, ×Si: crossbreed Simmental, Fin: final slaughter (n = 30), Ser: serial slaughter (additional n = 36). Single full grey line: linear regression for final plus serial slaughter, where intercept is not different according to crossbreed ($P > 0.10$). Three dotted black lines: linear regressions for final slaughter, where intercept is different ($P \leq 0.05$) according to crossbreed (— — ×Angus, - - - ×Limousin, · · · · · ×Simmental).

of carcass water mass from 11th rib dissection were reported for Friesian and Charolais bulls, compared to Salers and Limousin ones (Robelin and Geay, 1975b), as well as for minerals and bones in Friesian, compared to Charolais or Limousin (Robelin and Geay, 1975b and 1976).

Conclusion

The present study confirms the value of the rib dissection technique to estimate both the EB and carcass chemical and tissue compositions. Precision is higher when BW or HCW, and carcass traits are available as additional predictive variates. The main interest in the rib dissection method is due to both high precision and low cost as it requires non-specific equipment, and moderate time needed for dissection (around 15 min per rib for a trained butcher). Specific drawbacks are the sensitivity of estimative equations to the animal category (breed or crossbreed effects on intercept), as well as the operator effect along the dissection procedure. To counteract the latter limitation, some authors adjusted their equations of comparable precision with chemical composition of single (De Campeneere et al., 1999; Fiems et al., 2005) or multiple rib cuts (Marcondes et al., 2012; Berndt et al., 2017) as an alternative to tissue dissection. Other non-destructive, fast, and cheap

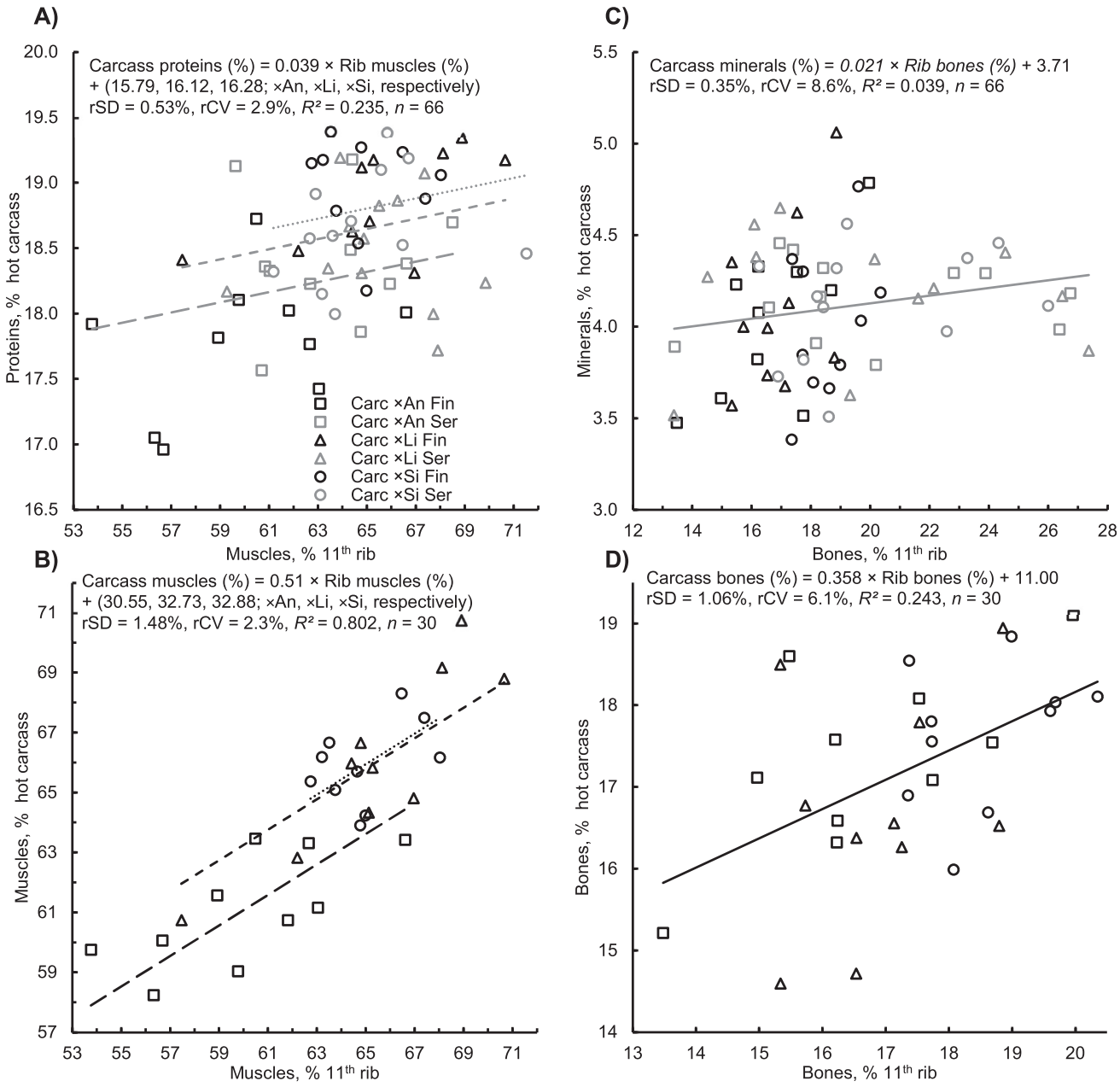

Fig. 3. Relationship between muscle proportion in the 11th rib and protein (A) and muscle (B) proportions in the hot carcass, and between bone proportion in the 11th rib and mineral (C) and bone (D) proportions in the hot carcass from crossbred growing bull. Carc: hot carcass, ×An: crossbreed Angus, ×Li: crossbreed Limousin, ×Si: crossbreed Simmental, Fin: final slaughter (n = 30), Ser: serial slaughter (additional n = 36). Single full grey or black lines: linear regressions for serial plus final, or only final slaughter, respectively where intercept is not different according to crossbreed ($P > 0.10$). Three dotted grey or black lines: linear regressions for serial plus final, or only final slaughter, respectively, where intercept is different ($P \leq 0.05$) according to crossbreed (— — ×Angus, - - - ×Limousin, · · · · · ×Simmental).

alternatives rely on rib cut imaging. For example, dual-energy X-ray absorptiometry (**DXA**) allowed precise estimation of the 9–11th rib cut tissue composition (Mitchell et al., 1997), whereas computer analysis of smartphone image of the 5–6th rib section was able to predict 6th rib tissue composition and intramuscular fat (Meunier et al., 2021). To the best knowledge of the authors, no attempt has been reported of calibration of imaging analysis of rib cut for estimations of the entire EB or carcass composition. Ideally, this step forward would have to also consider the effect of animal category (sex and breed or crossbreed) at the calibration and validation stages to allow the efficient use of the new sets of equations.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.57745/EK4FFP.

Ethics approval

All procedures performed on animals were approved by the ethics committee of the Fribourg cantonal state (no. 2016_48_FR and 2020_03_FR).

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Declaration of interest

The authors have no conflict of interest to declare.

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References

Alhassan, W.S., Buchanan-Smith, J.G., Usborne, W.R., Smith, G.C., Ashton, G.C., 1975. Predicting empty body composition of cattle from carcass weight and rib cut composition. Canadian Journal of Animal Science 55, 369–376.

Berndt, A., Lanna, D.P.D., Da Cruz, G.M., Tullio, R.R., Sakamoto, L.S., De Alencar, M.M., 2017. Prediction of the chemical body composition of Nellore and crossbreed bulls. Journal of Animal Science 95, 3932–3939.

Berry, D.P., 2021. Invited review: Beef-on-dairy—The generation of crossbred beef × dairy cattle. Journal of Dairy Science 104, 3789–3819.

Bocquier, F., Guillouet, P., Barillet, F., Chilliard, Y., 1999. Comparison of three methods for the in vivo estimation of body composition in dairy ewes. Annales De Zootechnie 48, 297–308.

De Campeneere, S., Fiems, L.O., Van De Voorde, G., Vanacker, J.M., Boucque, C.V., Demeyer, D.I., 1999. Estimation of chemical carcass composition from 8th rib characteristics with Belgian blue double-muscled bulls. Meat Science 51, 27–33.

Faverdin, P., Guyomard, H., Puillet, L., Forslund, A., 2022. Animal board invited review: Specialising and intensifying cattle production for better efficiency and less global warming: contrasting results for milk and meat co-production at different scales. Animal 16, 100431.

Fiems, L.O., Van Caelenbergh, W., Vanacker, J.M., De Campeneere, S., Seynaeve, M., 2005. Prediction of empty body composition of double-muscled beef cows. Livestock Production Science 92, 249–259.

Friggens, N.C., Blanc, F., Berry, D.P., Puillet, L., 2017. Review: Deciphering animal robustness. A synthesis to facilitate its use in livestock breeding and management. Animal 11, 2237–2251.

Geay, Y., Beranger, C., 1969. Estimation de la composition de la carcasse de jeunes bovins à partir de la composition d'un morceau monocostal au niveau de la 11ème côte. Annales De Zootechnie 18, 65–77.

Hankins, O.G., Howe, P.E., 1946. Estimation of the composition of beef carcasses and cuts. Technical Bulletin USDA, 926; 20 pp.

Kearney, M., O'Riordan, E.G., McGee, M., Breen, J. Crosson, P., 2022. Farm-Level Modelling of Bioeconomic, Greenhouse Gas Emissions and Feed-Food Performance of Pasture-Based Dairy-Beef Systems. Available from SSRN: https://ssrn.com/abstract=4188403 or https://doi.org/10.2139/ssrn.4188403.

Kenny, D.A., Fitzsimons, C., Waters, S.M., McGee, M., 2018. Invited review: Improving feed efficiency of beef cattle – the current state of the art and future challenges. Animal 12, 1815–1826.

Kuhn, M., 2021. Caret: Classification and regression training. R package version 6.0-90. Available from https://github.com/topepo/caret/.

Lerch, S., Oberson, J.L., Silacci, P., Morel, I., 2020. Performances du système d'alimentation suisse «Livre vert» pour le bovin à l'engrais. Recherche agronomique suisse 11, 252–260.

Lerch, S., De La Torre, A., Huau, C., Monziols, M., Xavier, C., Louis, L., Le Cozler, Y., Faverdin, P., Lamberton, P., Chery, I., Heimo, D., Loncke, C., Schmidely, P., Pires, J. A.A., 2021. Estimation of dairy goat body composition: A direct calibration and comparison of eight methods. Methods 186, 68–78.

Marcondes, M.I., Tedeschi, L.O., Valadares Filho, S.C., Chizzotti, M.L., 2012. Prediction of physical and chemical body compositions of purebred and crossbred Nellore cattle using the composition of a rib section. Journal of Animal Science 90, 1280–1290.

Meunier, B., Normand, J., Albouy-Kissi, B., Micol, D., El Jabri, M., Bonnet, M., 2021. An open-access computer image analysis (CIA) method to predict meat and fat content from an android smartphone-derived picture of the bovine 5th-6th rib. Methods 186, 79–89.

Mitchell, A.D., Solomon, M.B., Rumsey, T.S., 1997. Composition analysis of beef rib sections by dual-energy X-ray absorptiometry. Meat Science 47, 115–124.

Monteils, V., Sibra, C., Ellies-Oury, M.P., Botreau, R., De La Torre, A., Laurent, C., 2017. A set of indicators to better characterize beef carcasses at the slaughterhouse level in addition to the EUROP system. Livestock Science 202, 44–51.

Proviande, 2005. CH-TAX Système d'estimation pour le bétail de boucherie et les carcasses (bovins, ovins), 19 pp.

R Core Team, 2020. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available from https://www.R-project.org/.

Robelin, J., 1973. Estimation de la composition corporelle des animaux à partir des espaces de diffusion de l'eau marquée. Annales de Biologie animale, Biochimie, Biophysique 13, 285–305.

Robelin, J., Geay, Y., 1975a. Estimation de la composition de la carcasse de taurillions à partir de la composition de la 6ème côte. Bulletin Technique C.R.Z. V. Theix 22, 41–44.

Robelin, J., Geay, Y., 1975b. Estimation de la composition de jeunes bovins à partir de la composition d'un morceau monocostal prélevé au niveau de la 11ème côte. I. Composition anatomique de la carcasse. Annales De Zootechnie 24, 391–402.

Robelin, J., Geay, Y., Béranger, C., 1975. Estimation de la composition chimique des carcasses de jeunes bovins mâles à partir de la proportion de dépôts adipeux d'un morceau moncostal prélevé au niveau de la 11ème côte. Annales De Zootechnie 24, 323–326.

Robelin, J., Geay, Y., 1976. Estimation de la composition des carcasses de jeunes bovins à partir de la composition d'un morceau monocostal prélevé au niveau de la 11ème côte. II. Composition chimique de la carcasse. Annales De Zootechnie 25, 259–272.

Scholz, A.M., Bunger, L., Kongsro, J., Baulain, U., Mitchell, A.D., 2015. Non-invasive methods for the determination of body and carcass composition in livestock: dual-energy X-ray absorptiometry, computed tomography, magnetic resonance imaging and ultrasound: invited review. Animal 9, 1250–1264.

Signorell, A. et al., 2022. DescTools: Tools for descriptive statistics. R package version 0.99.45. Available from: https://cran.r-project.org/package=DescTools.

Speakman, J.R., 2001. Body composition analysis of animals: a handbook of non-destructive methods. Cambridge University Press, Cambridge, UK.

Tedeschi, L.O., 2006. Assessment of the adequacy of mathematical models. Agricultural Systems 89, 225–247.

Xavier, C., Driesen, C., Siegenthaler, R., Dohme-Meier, F., Le Cozler, Y., Lerch, S., 2022. Estimation of empty body and carcass chemical composition of lactating and growing cattle: comparison of imaging, adipose cellularity, and rib dissection methods. Translational Animal Science 6.