Meat Science 213 (2024) 109503

Contents lists available at ScienceDirect

Meat Science

journal homepage: www.elsevier.com/locate/meatsci

Beef-on-dairy: Meat quality of veal and prediction of intramuscular fat using the Q-FOM™ Beef camera at the 5th–6th thoracic vertebra

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ARTICLE INFO

Keywords:
Crossbreeding
Angus
Charolais
Danish blue
M. longissimus thoracis
Objective grading

ABSTRACT

This study aims to describe the meat quality of young Holstein (HOL) beef-on-dairy heifers and bulls sired by Angus (ANG, $n = 109$), Charolais (CHA, $n = 101$) and Danish Blue (DBL, $n = 127$), and to investigate the performance of the handheld vision-based Q-FOM™ Beef camera in predicting the intramuscular fat concentration (IMF%) in *M. longissimus thoracis* from carcasses quartered at the 5th–6th thoracic vertebra. The results showed significant differences between crossbreeds and sexes on carcass characteristics and meat quality. DBL × HOL had the highest EUROP conformation scores, whereas ANG × HOL had darker meat with higher IMF% (3.52%) compared to CHA × HOL (2.99%) and DBL × HOL (2.51%). Bulls had higher EUROP conformation scores than heifers, and heifers had higher IMF% (3.70%) than bulls (2.31%). These findings indicate the potential for producing high-quality meat from beef-on-dairy heifers and ANG bulls. The IMF% prediction model for Q-FOM performed well with $R^2 = 0.91$ and root mean squared error of cross validation, RMSECV = 1.33%. The performance of the prediction model on the beef-on-dairy veal subsample ranging from 0.9 to 7.4% IMF had lower accuracy ($R^2 = 0.48$) and the prediction error ($RMSE_{veal}$) was 1.00%. When grouping beef-on-dairy veal carcasses into three IMF% classes (2.5% IMF bins), 62.6% of the carcasses were accurately predicted. Furthermore, Q-FOM IMF% predictions and chemically determined IMF% were similar for each combination of sex and crossbreed, revealing a potential of Q-FOM IMF% predictions to be used in breeding, when aiming for higher meat quality.

1. Introduction

In Denmark, cattle originating from dairy herds are the main contributor to beef production, and in recent years beef-on-dairy crossbreeding has increased considerably, improving feed efficiency, carcass weight, EUROP conformation, meat yield, and meat quality compared with purebred dairy offspring (Bittante et al., 2021; Davis, Fikse, Carlén, Pösö, & Aamand, 2019; Gariepy, Seoane, Cloteau, Martin, & Roy, 1999; Keane, 2011; Sørensen et al., 2018; Vestergaard et al., 2019). Danish Blue (DBL) is the most common choice for beef-on-dairy crossbreeding in Denmark as a Danish subline of the double muscled Belgian Blue (BBL) with a focus on natural calving (Davis et al., 2019; Sørensen et al., 2018). Despite the higher carcass weights and EUROP conformations of DBL × Holstein (HOL) compared with purebred HOL and other HOL crossbreeds (Hickey, Keane, Kenny, Cromie, & Veerkamp, 2007; Keady et al., 2017; Keane & Moloney, 2009), Charolais (CHA) × Friesian and Angus (ANG) × HOL is reported to have higher intramuscular fat concentration (IMF%) than BBL × HOL (Gagaoua et al., 2016; Keady et al., 2017). IMF% is highly correlated with juiciness, tenderness, and overall liking of beef (Cheng, Cheng, Sun, & Pu, 2015; Savell et al., 1987), making it a good indicator of overall meat quality (Liu et al., 2020b; O'Quinn, Legako, Brooks, & Miller, 2018). It has previously been established that IMF% is heritable (Halli, Bohlouli, Schulz, Sundrum, & König, 2022; Torres-Vázquez & Spangler, 2016).

Beef carcass grading in Europe does not include IMF% or marbling scores. Several studies have reported no or negative relationships between EUROP conformation or fatness scores and IMF%, marbling, sensory tenderness, juiciness, flavour liking and overall liking (Bonny et al., 2016; Guzek, Glabska, Gutkowska, & Wierzbicka, 2016; Liu et al., 2020a; Nogalski, Pogorzelska-Przybyłek, Sobczuk-Szul, & Purwin,

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https://doi.org/10.1016/j.meatsci.2024.109503
Received 1 November 2023; Received in revised form 12 March 2024; Accepted 25 March 2024

2019). This empathises the unexploited meat quality potentials of some crossbreeds. IMF% is normally determined by chemical analysis in the laboratory and it is an expensive and laborious analysis, requiring removal of a meat sample from the *M. longissimus thoracis* (LT) – a muscle with high economic importance. The ability to predict IMF% in the LT muscle directly on the cut surface of the carcass at the slaughterhouse is therefore needed if this trait should potentially be included in carcass grading and affect beef market pricing based on meat quality.

One opportunity is the use of camera solutions with visible light. Whereas EUROP classification is performed on half carcasses, determination of the IMF% in LT requires that the carcass is cut open to expose the eye muscle cross-sectional cut surface. In most slaughterhouses in Europe, carcasses are quartered between 5th and 6th thoracic vertebra, whereas the Australian and American beef carcasses are usually quartered at the 10th to 13th rib. Previous studies have demonstrated good or moderate predictions of IMF% with camera solutions, at the dominating carcass quartering site 12th–13th rib (Pannier, van de Weijer, van der Steen, Kranenbarg, & Gardner, 2023b; Peña, Molina, Avilés, Juárez, & Horcada, 2013; Stewart et al., 2021; Stewart et al., 2021). Stewart, Lauridsen, et al. (2021) performed a study in which a prototype camera (Frontmatec Smoerum A/S Denmark) showed promising results regarding prediction of IMF%, but both hardware and software needed refinements prior to commercialisation. A new objective carcass grading camera, Q-FOM™ Beef, was launched in 2022. This study is the first to report the ability of Q-FOM to predict IMF% in LT at the 5th–6th thoracic vertebra.

The majority of beef-on-dairy in Denmark is sold as rosé veal (slaughter age 8–11 months) to fit the financially prudent brand “Dansk Kalv” (Danish Crown, 2023). Thus, when aiming for non-destructive real-time prediction of IMF%, a high accuracy and precision is essential to distinguish between the low to medium marbled carcasses in Denmark. With an acceptable performance of the prediction model, it is foreseen that Q-FOM can distinguish between crossbreeds and thereby offer valuable insights for farmers and breeding programs in supporting the breeding towards higher meat quality.

The aims of this research were to evaluate the meat quality of LT from crossbred HOL bull and heifer calves sired by ANG, CHA and DBL. Additionally, the ability of Q-FOM to predict IMF% in LT of these veal carcasses quartered at the 5th–6th thoracic vertebra was evaluated.

2. Materials and methods

2.1. Animals and slaughter

A total of 337 crossbred calves from HOL dams sired by 16 ANG bulls ($n = 109$), 14 CHA bulls ($n = 101$) and 26 DBL bulls ($n = 127$) were studied. The calves were born in Denmark in dairy herds between October 2020 and September 2021 and commenced their rearing on three specialized rosé veal farms at the age of 3–8 weeks. All calves were fed ad libitum, with herd 1, and 3 receiving a feed concentrate and herd 2 receiving a total mixed ration (Table 1). Calves were slaughtered at ages 8–11 months (depending on live weight) according to the “Dansk Kalv” brand (Danish Crown, 2023). In addition, samples from 103 carcasses with visible high marbling were collected and included as reference samples to support the development of a Q-FOM IMF% prediction algorithm representative of a broader IMF% span. Descriptive statistics on reference carcasses are given in Table 2. All animals were transported to the commercial slaughter plant (Danish Crown, Holsted, Denmark), and slaughtered within 1 h of arrival by stunning with a captive bolt, followed by bleeding and electrical stunning (100 V for 400 s). The calves were transported 23 km, 89 km, and 167 km to the slaughterhouse from herd 1, 2, and 3, respectively. The carcasses were split in halves and hung by achilles suspension at 2 °C. EUROP fatness and conformation was evaluated by BCC-3™ beef classification system (Frontmatec Smoerum A/S Denmark).

Table 1
Distribution of beef-on-dairy calves in three rosé veal herds, with feed composition used in each herd.

	Herd 1	Herd 2	Herd 3
n	117	121	99
Dry matter (DM) (%)	87.90	48.45	86.90
Crude protein (g/kg DM)	188.1	165.5	172.7
Crude fat (g/kg DM)	35.25	25.85	33.00
Ash (g/kg DM)	62.38	54.08	64.67
Neutral detergent fibre (g/kg DM)	183.3	236.7	211.0
Starch (g/kg DM)	436.5	395.1	415.3
Fill value	0.22	0.26	0.22
Net Energy (MJ/kg DM)	7.741	7.387	7.533

2.2. Sampling and image acquisition

One day *post-mortem*, the half carcasses were divided into forequarter and hindquarter by quartering between the 5th and 6th thoracic vertebra. The carcasses were allowed to bloom for 20 to 30 min at 4 °C before images of the cut surface of LT were acquired in-chiller by Q-FOM™ Beef (Frontmatec Smoerum A/S, Denmark). Any excessive bone dust and fat smear present on the cut surface was removed by the camera operator prior to image acquisition. Following image acquisition, a 7-cm (equivalent to the width of two ribs) cross-sectional sample containing LT were collected from the right side of the carcass by an experienced butcher. These samples were transported on ice to the meat laboratory at Aarhus University. The samples were stored at 5 °C until *post-mortem* day 3 and then analysed for meat quality traits. LT was removed from the surrounding muscle tissue and two subsamples of 1 cm and 5 cm were cut from the caudal end.

2.3. Meat colour and pH

The fresh cut 1-cm samples bloomed for 30 min before colour was measured at three sites per steak with a Chroma Meter CR-400 (Konica Minolta, Osaka, Japan) which was equipped with an 8 mm measuring diameter and 2° illumination angle (CIE standard illuminant C), calibrated against a white plate provided by the manufacturer. The average CIE 1976 values (L^*, lightness; a^*, redness; b^*, yellowness) were recorded. Afterwards, the colour samples were vacuum packed and frozen at −20 °C for later determination of IMF%. Ultimate pH (3 d *post-mortem*) was measured in duplicates in the 5-cm samples with a Metrohm 826 mobile pH meter equipped with a Metrohm spearhead glass electrode (Metrohm, Herisau, Switzerland) calibrated in pH 4.005 and 7.000 IUPAC buffers (Hach Lange, Germany). Average sample pHs were recorded, and samples were used immediately for Warner-Bratzler shear force (WBSF) analyses.

2.4. Warner-Bratzler shear force and cooking loss

Warner-Bratzler shear force was measured on fresh meat samples 3

Table 2
Descriptive statistics on carcass characteristics and intramuscular fat concentration (IMF%) for the 103 reference carcasses included in the prediction model (raw means with standard deviations, SD, minimum and maximum values).

	Mean	SD	Min	Max
Slaughter age (d)	1784	753	257	4036
Slaughter weight (kg)	329	63	199	508
EUROP conformation[1]	3.82	1.18	2.13	8.32
EUROP fatness[1]	3.28	0.62	2	5
LT area (cm^2)[2]	29.77	5.79	17.85	47.28
Chemical IMF%	11.80	3.68	1.23	22.90

[1] EUROP scores on a scale 1–15 for conformation and 1–5 for fatness.

[2] LT area = cross sectional area of *M. longissimus thoracis* at 5th–6th thoracic vertebra.

d *post-mortem*. Samples were cut to size (5 × 4 × 8 cm), weighed, vacuum packed, and heat treated in circulating water (10 min at 4 °C, 60 min at 62 °C, and 30 min at 4 °C). For each analysis day, a maximum of 15 samples per heating batch were randomly selected from the sample pool. Samples were rinsed with water, blotted dry with clean paper towels, and weighed again to determine the cooking loss, defined as the percentage weight loss of the samples after cooking relative to prior cooking. Four 1-cm slices were cut from each sample on an electric food slicer, and a 1-cm-wide strip was cut from each slice parallel to the muscle fibres to yield four replicates (size 4 × 1 × 1 cm) per sample for analysis on the TMS-Pro Texture Analyser equipped with a 1000 N load cell (Food Technology Corporation, Sterling, Virginia, USA). The analysis was carried out at a speed of 48 mm/min using a square Warner-Bratzler shear blade (11 mm wide, 15 mm tall, 1.2 mm thick) for shearing of the meat strips across the fibres. The mean maximum force of replicates was recorded.

2.5. *Chemical intramuscular fat concentration*

Samples (40–50 g) for IMF analyses were thawed for 1 h at room temperature or overnight at 5 °C. The intermuscular fat and visible connective tissue were removed and discarded, and the meat slices were cut into smaller pieces and homogenized in a small food processor. A subsample of 9.5 ± 0.5 g was weighed from each sample, and IMF was extracted using a combination of the closed system apparatuses HYDROTHERM (ISO 8262-1 Weibull-Berntrop gravimetric method) and SOXTHERM® (rapid soxhlet extraction) according to the procedure described by Gerhardt (C. Gerhardt GmbH & Co. KG, Königswinter, Germany). IMF% was determined from the amount of fat extracted relative to the sample weight.

2.6. *Q-FOM™ Beef camera*

The Q-FOM is a vision system comprised by a high resolution 2D camera in combination with a 3D camera, that enables correct colour and area representation, whilst maintaining high resolution of the LT area (eye muscle area). Two high intensity diffused LED panels are utilised to illuminate the cut surface during image acquisition, minimizing negative effects of ambient light. Subsurface scattering occurs due to the semi-transparent nature of soft tissue. All scattered light is collected by an RGB sensor. Subsurface scattering is implicitly handled in the clustering analysis. A depth sensitive viewfinder guides the camera operator to the optimal imaging distance and angles, to eliminate camera operator influence on measurements.

2.7. *Image processing and analysis*

2.7.1. *Segmentation of M. longissimus thoracis area*

The boundary of the LT muscle in the cut graded surface is identified using deep learning based semantic segmentation (Ulku & Akagündüz, 2022). The model was trained to find three objects namely: the entire cut surface, the undamaged LT muscle, and any damaged LT muscle if present. Manual annotations were performed on 2175 images, of which 80% ($n = 1740$) were used for training of the segmentation model. This model was then applied to the remaining images ($n = 435$). Visual inspection of LT trace was performed to evaluate the segmentation model performance.

2.7.2. *Standardization of images and measurement of M. longissimus thoracis area*

The image analysis software standardizes the images according to a set of calibration parameters recorded during the Q-FOM manufacturing process. A subset of the calibration parameters is used to colour, and intensity correct the images. The intensity correction depends on the depth and angle of each point on the cut surface. Subsequently, the cut surface is perspective transformed to be presented as if it were viewed top-down at a fixed distance. The number of pixels within the LT segmentation (as described in section 2.7.1.) is then converted to LT area using a constant scaling factor that depends on the fixed distance.

2.7.3. *Colour segmentation and feature extraction*

The LT muscle region is further segmented into meat and fat clusters using a Gaussian Mixture Model algorithm (Reynolds, 2009) and the colour statistics (average colour intensity etc.) of each of these segmentation clusters is computed. The total fat area in relation to the LT area is measured. To quantify the distribution of intramuscular fat the average distance from any point in the segmented LT to any fat pixel is calculated. All the above measures may be considered as entries in a vector of feature descriptors.

2.8. *Statistical analysis*

2.8.1. *Q-FOM™ Beef prediction model for intramuscular fat concentration*

The calibration of IMF% was performed by multivariate data analysis. The data were centred and scaled to unit variance. Partial Least Squares (PLS) regression was used to predict IMF%. To optimize the PLS model, only feature descriptors correlating with IMF% or providing objectively meaningful information are included in the model. The optimal number of components is selected using five-fold cross-validation in combination with the “One-standard-error rule” (Hastie, Tibshirani, Friedman, & Friedman, 2009) to avoid over fitting. The PLS toolbox 8.7.1. (Eigenvector Research, Manson, USA) with Matlab R2021a (Mathworks, Natick, USA) was used for analysis.

The calibration performance was evaluated using the squared Pearson correlation (R^2) and root mean squared error of the cross-validation (RMSECV) for the relationship between actual versus predicted. Obvious reference outliers or outliers caused by poor image quality were discarded from the calibration dataset. Maximum and minimum limits on the individual feature descriptors were determined to avoid extrapolating the model beyond the calibration dataset extreme values.

The model performance on IMF% predictions for rosé veal was tested by reporting R^2 of the prediction and root mean squared error on the beef-on-dairy veal subsample ($RMSE_{veal}$). Classification performance on the veal subsample using the full IMF prediction model was demonstrated in a confusion table with 3 bins of 2.5% IMF width.

2.8.2. *Statistical analysis of carcass and meat quality data*

Data analysis was performed in R software (v4.2.2). Data was checked for normality by Shapiro-Wilk's test and the response variable was transformed where necessary to fit the assumption of normality. Assumption of normality was violated for EUROP fatness, cooking loss, LT area and predicted IMF%. EUROP fatness took values 2 and 3 and was recoded to take values 0 and 1 and then interpreted as a binomial generalized linear mixed model using the glmer function, from package lme4. Cooking loss, LT area and predicted IMF% was fitted as a generalized linear mixed model with gamma distribution using the glmer function, from package lme4. The remaining response variables were fitted as linear mixed models using the lmer function, from package lme4. All models included fixed effects of sex and crossbreed and their interaction, as well as the covariate effect of slaughter age (except for response variable slaughter age) and a random effect of herd and sire. Models for cooking loss and WBSF furthermore included a random effect of cooking batch (batch = 1, 2, …, 38). Type II Wald chi-square tests were conducted for lmer fitted models using the Anova function, from package car. The binomial and gamma glmer models were tested by likelihood ratio test of nested models using lrtest function, from package lmtest. Fixed effects were identified as significant if the associated *P*-value was lower than 0.05. The emmean package was used to generate least-squares means (LSmeans) and standard error of the mean (SEM) for all response variables and reported on original scales. Group differences were tested for significance with Tukey-Kramer method for a family of six estimates at 0.05 significance level using the cld function, from package multcomp.

3. Results

3.1. Carcass characteristics and meat quality of beef-on-dairy calves

The carcass characteristics of beef-on-dairy calves are presented in Table 3 revealing significant differences between crossbreeds and sexes in all traits. DBL × HOL are slaughtered later and have higher slaughter weights and EUROP conformation scores than ANG × HOL and CHA × HOL. There is furthermore a trend that DBL × HOL scores higher on LT area than CHA × HOL, which scores higher than ANG × HOL. On the contrary, ANG × HOL bulls scores higher on EUROP fatness than DBL × HOL bulls. With regards to sex, heifers are slaughtered later than bulls, and have lower slaughter weights, LT areas, and EUROP conformation scores. Heifers score higher than bulls on EUROP fatness.

Meat quality also differed significantly between crossbreeds and sexes on most traits (Table 4). The pH measured in LT 72 h *post-mortem* was between 5.59 and 5.63, with small differences between crossbreeds and sexes, although some differences are significant. ANG × HOL has darker meat with higher IMF% than the other crossbreeds, but also higher WBSF. CHA × HOL bulls seem to group with ANG × HOL on lightness and cooking loss, where CHA × HOL heifers are similar to DBL × HOL with lighter meat and lower cooking loss. Differences in cooking loss, however, were not significant. Breeds did not differ in redness and yellowness. WBSF values were similar between CHA × HOL and DBL × HOL, whereas WBSF values in rosé veal from ANG × HOL calves were higher. In general, the breed difference on WBSF is small, with the only significant differences being between ANG × HOL bulls and CHA × HOL heifers, although the interaction between breed and sex is non-significant. For chemical IMF%, meat from DBL × HOL exhibits a lower level than both ANG × HOL and CHA × HOL, ranking the crossbreeds ANG × HOL > CHA × HOL > DBL × HOL. The meat from heifers is lighter, redder, yellower, has lower WBSF and higher chemical IMF% compared with bulls. Additionally, there was a tendency for lower cooking losses in heifers compared with bulls ($P = 0.057$).

3.2. Performance of Q-FOM™ Beef prediction model for intramuscular fat concentration

As seen from Table 2 the span in IMF% of reference carcasses ranges from 1.23 to 22.90 IMF%. This broad IMF range was deliberately chosen to enable development of an IMF% model representing a broad IMF% range. The relationship between IMF% measured by chemical analysis and predicted by Q-FOM is shown in Fig. 1.

The accuracy and precision of the Q-FOM calibration and cross-validated model for predicting chemical IMF% in LT at 5th–6th thoracic vertebra is given in Table 5. The Q-FOM algorithm demonstrated a high level of accuracy ($R^2 = 0.91$) and a good precision ($RMSECV = 1.33\%$). The RMSECV is very close to the root mean squared error of calibration, $RMSEC = 1.31\%$, indicating that a prediction error of this magnitude is to be expected when applying the model on unknown samples.

Calculation of the prediction error and R^2 of the beef-on-dairy veal subsample indicate that only 48% of the variation is explained by the model within this subsample. The prediction error for the veal subsample ($RMSE_{veal}$) is 1.00% and is numerically smaller than the prediction error (RMSECV) found for the model spanning the IMF% range 0.9–22.9%.

Calculations reveal that 59.4% of the carcasses in the full model and 62.6% of the carcasses in the veal subsample are accurately predicted by Q-FOM when compared to the chemical IMF% reference if 2.5% IMF bins are used to classify the carcasses. Table 6 shows the veal subsample confusion table for IMF%.

The chemical and predicted IMF% of the subsample of beef-on-dairy calves ranging in IMF from 0.9 to 7.4 IMF% are given in Table 7. It is evident that the significance of crossbreed and sex is repeated in the model, along with the non-significance of their interaction. Furthermore, the Tukey test reveal similar differences between beef-on-dairy groups of the chemical and predicted IMF% values, with the only deviance in DBL × HOL heifers.

4. Discussion

4.1. Carcass characteristics of beef-on-dairy calves

This study demonstrates the significance of sire breed in young beef-on-dairy calves on carcass characteristics and meat quality of LT. DBL × HOL produced carcasses with higher EUROP conformation scores and a trend towards higher LT areas than CHA × HOL and ANG × HOL. This might be explained by the double muscling of DBL, causing hypertrophy (a greater cross-sectional area of all fibre types), and hyperplasia (increased number of muscle fibres) as well as more numerous glycolytic fibres compared with oxidative fibres (Bittante et al., 2018; Fiems, 2012). These findings are also consistent with the relationships between breed maturities (Keane & Drennan, 2008), and previous research. Keane and Moloney (2009) found that BBL × Holstein-Friesian had a larger LT area than ANG × Holstein-Friesian, and Sinclair et al. (2001) found that purebred CHA had a larger LT area than ANG. Both findings were made at the 10th rib in contrast to our findings at the 5th–6th thoracic vertebra.

In the present study, the significant effect of breed on slaughter

Table 3
Carcass characteristics of beef-on-dairy heifer and bull calves from Holstein (HOL) dams sired by Angus (ANG), Charolais (CHA) and Danish Blue (DBL) presented as least-squares means, standard error of the mean (SEM) and *P*-values.

Crossbreed (B)	ANG × HOL		CHA × HOL		DBL × HOL		SEM	*P*-values		
Sex (S)	Bulls	Heifers	Bulls	Heifers	Bulls	Heifers		B	S	B × S
n	65	44	54	47	56	71	–	–	–	–
Slaughter age (d)[2]	277^{ab}	292^{cd}	271^{a}	292^{bc}	287^{bc}	306^{d}	3.94	<0.001	<0.001	0.555
Slaughter weight (kg)[2]	221^{b}	195^{a}	234^{c}	204^{a}	228^{bc}	202^{a}	5.84	0.001	<0.001	0.359
EUROP conformation[1,2]	6.22^{bc}	5.56^{a}	6.76^{cd}	6.16^{ab}	7.94^{e}	6.94^{d}	0.21	<0.001	<0.001	0.264
EUROP fatness[1,3]	2.85^{bc}	3.02^{c}	2.62^{ab}	2.98^{c}	2.45^{a}	2.99^{c}	0.06	<0.001	<0.001	0.751
n	59	42	46	45	48	54	–	–	–	–
LT area (cm^2)[4,5]	30.7^{b}	27.2^{a}	31.7^{bc}	29.8^{ab}	34.4^{c}	32.8^{bc}	1.4	0.010	<0.001	0.229

[a-d] Tukey test: Values within a row with different superscripts differ significantly at $P < 0.05$.

[1] EUROP scores on a scale 1–15 for conformation and 1–5 for fatness.

[2] Gaussian model with *P*-values obtained from Type II Wald Chi-Squared Analysis of Variance (ANOVA).

[3] Binomial model with *P*-values obtained from likelihood ratio tests.

[4] Gamma model with *P*-values obtained from likelihood ratio tests.

[5] LT area = cross sectional area of *M. longissimus thoracis* measured by Q-FOM™ Beef at 5th–6th thoracic vertebra. The lower number of samples for LT area is due to not all carcasses being imaged with the Q-FOM.

Table 4
Meat quality of *M. longissimus thoracis* beef-on-dairy heifer and bull calves from Holstein (HOL) dams sired by Angus (ANG), Charolais (CHA) and Danish Blue (DBL) presented as least-squares means, standard error of the mean (SEM) and *P*-values.

Crossbreed (B)	ANG × HOL		CHA × HOL		DBL × HOL		SEM	*P*-values		
Sex (S)	Bulls	Heifers	Bulls	Heifers	Bulls	Heifers		B	S	B × S
n[1]	65	44	54	47	56	71	–	–	–	–
pH[2]	5.63^{b}	5.60^{ab}	5.62^{ab}	5.63^{b}	5.61^{ab}	5.59^{a}	0.01	0.012	0.027	0.038
L^*[2,4]	47.6^{a}	48.0^{abc}	48.6^{abd}	50.7^{ce}	50.4^{bcde}	50.9^{de}	0.7	<0.001	0.035	0.107
a^*[2,4]	23.4^{ab}	23.9^{ab}	23.4^{ab}	23.9^{ab}	22.8^{a}	24.1^{b}	0.3	0.822	<0.001	0.185
b^*[2,4]	11.4^{ab}	12.0^{ab}	11.4^{a}	12.5^{b}	11.7^{ab}	12.5^{ab}	0.4	0.591	<0.001	0.468
Cooking loss (%)[3]	11.9^{c}	11.5^{abc}	11.7^{bc}	10.4^{abc}	10.0^{a}	9.9^{ab}	0.5	0.184	0.057	0.139
WBSF (N)[2,5]	54.8^{b}	49.1^{ab}	49.6^{ab}	46.6^{a}	51.1^{ab}	46.7^{a}	1.9	0.047	<0.001	0.774
IMF%[2,6]	2.96^{bc}	4.70^{d}	2.37^{ab}	3.56^{c}	1.67^{a}	2.74^{b}	0.24	<0.001	<0.001	0.437

[a-d] Tukey test: Values within a row with different superscripts differ significantly at $P < 0.05$.
[1] $n = 54$ for cooking loss, and $n = 55$ for WBSF in DBL × HOL heifers.
[2] Gaussian model with *P*-values obtained from Type II Wald Chi-Squared Analysis of Variance (ANOVA).
[3] Gamma model with *P*-values obtained from likelihood ratio tests.
[4] L^* (lightness), a^* (redness), b^* (yellowness) measured on CIE 1976 $L^*a^*b^*$ scale.
[5] WBSF = Warner Bratzler shear force, maximum force.
[6] IMF% = Intramuscular fat concentration in percent assessed by chemical analysis in the laboratory.

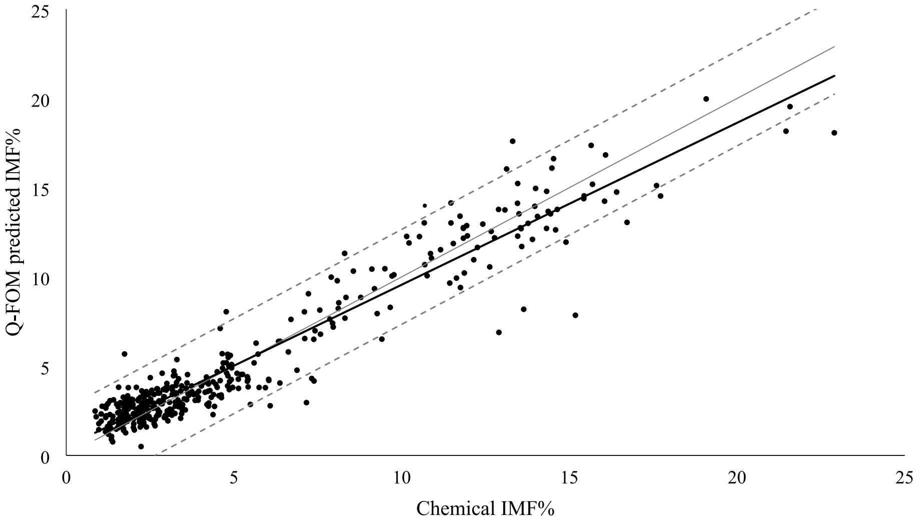

Fig. 1. Regression plot of the Q-FOM™ Beef predicted intramuscular fat concentration (IMF%) against the reference chemical IMF% of *M. longissimus thoracis* at the 5th–6th thoracic vertebra. Dots represent individual carcass observations ($n = 397$), and the solid black line is the regression line. The solid grey line represents the 1:1 relationship, whereas the dashed grey lines represent the 95% confidence intervals calculated as ±2*RMSECV.

Table 5
Accuracy and precision for the Q-FOM™ Beef calibration model, the cross-validated model and the beef-on-dairy veal subsample when predicting intramuscular fat concentration (IMF%) of *M. longissimus thoracis* at 5th–6th thoracic vertebra. Coefficient of determination (R^2) prediction errors, and Raw means with standard deviations (SD) for the reference chemical data are shown.

		Prediction model		Chemical IMF%	
	n	R^2	Prediction error	Range	Mean ± SD
Calibration model[1]	397	0.91	1.31	0.9–22.9	5.28 ± 4.45
Cross validation model[2]	397	0.91	1.33	0.9–22.9	5.28 ± 4.45
Veal subsample[3]	294	0.48	1.00	0.9–7.4	3.00 ± 1.38

[1] Prediction error given as root mean squared error of calibration (RMSEC).
[2] Prediction error given as root mean squared error of five-fold cross validation (RMSECV).
[3] Prediction error calculated as root mean squared error for the veal subsample ($RMSE_{veal}$).

Table 6
Confusion table for intramuscular fat concentration (IMF%) showing the number of correctly classified (diagonal, $n = 184$, constituting 62.6%) and misclassified carcasses (outside the diagonal, $n = 110$, constituting 37.4%) of the veal subsample by Q-FOM™ Beef. The total number of carcasses in each bin is given in the right column.

		Q-FOM predicted IMF%			Total number of carcasses
		0.00–2.50	2.51–5.00	5.01–7.50	
Chemical IMF%	5.01–7.50		20	5	25
	2.51–5.00	21	104	9	134
	0.00–2.50	75	59	1	135

weight ($P = 0.001$) is not very pronounced between groups, but differences may have been more distinct if the animals had been older. Other studies with older animals found that BBL and BBL crossbreeds have higher slaughter weights than ANG and ANG crossbreeds, and that BBL and CHA crossbreeds have similar slaughter weights (Hickey et al., 2007; Keady et al., 2017; Keane & Drennan, 2008; Keane & Moloney, 2009). These studies also found that EUROP conformation was higher and EUROP fatness was lower in BBL and BBL crossbreeds than in ANG

Table 7

Chemical intramuscular fat concentration (IMF%) and Q-FOM™ Beef predicted IMF% of beef-on-dairy calves from Holstein dams sired by Angus (ANG), Charolais (CHA) and Danish Blue (DBL) (least-squares means and standard error of the mean, SEM).

Crossbreed (B)	ANG × HOL		CHA × HOL		DBL × HOL		SEM	*P*-values		
Sex (S)	Bulls	Heifers	Bulls	Heifers	Bulls	Heifers		B	S	B × S
n	59	42	46	45	48	54	–	–	–	–
Chemical IMF%[1]	2.85^{bc}	4.68^{d}	2.40^{ab}	3.57^{c}	1.75^{a}	2.68^{b}	0.24	<0.001	<0.001	0.320
Q-FOM IMF%[2]	3.07^{bc}	4.21^{d}	2.57^{ab}	3.35^{c}	2.28^{a}	2.96^{bc}	0.19	<0.001	<0.001	0.635

[a-d] Tukey test: Values within a row with different superscripts differ significantly at $P < 0.05$.

[1] Gaussian model with *P*-values obtained from Type II Wald Chi-Squared Analysis of Variance (ANOVA).

[2] Gamma model with *P*-values obtained from likelihood ratio tests.

and ANG crossbreeds, which is consistent with our results. This can be explained by the early maturation of ANG compared with BBL, resulting in smaller carcasses and earlier fat deposition (Keane & Drennan, 2008). However, at this age, even the earlier maturing ANG × HOL is not yet matured, which may be the reason behind the non-significant relationship between ANG × HOL and the later maturing CHA × HOL on EUROP fatness. In studies of young bulls and steers, purebred CHA has higher slaughter weights and lower EUROP fatness scores than purebred ANG, with no differences between breeds on EUROP conformation (Ripoll et al., 2018; Sinclair et al., 2001), indicating that crossbreeding with HOL reduces the variation between the sire breeds, and thus the effects of breed maturity, and other unique traits such as double muscling. Consequently, the main finding on carcass characteristics in the young beef-on-dairy calves was the difference in EUROP conformation between crossbreeds, while many other carcass characteristics are similar across crossbreeds due to the low slaughter age and reduced genetic effects of sire breeds resulting from crossbreeding with HOL.

The effects of sex on carcass characteristics are in agreement with previous findings, reporting lower slaughter weights, lower EUROP conformation scores and higher EUROP fatness scores in heifers compared with bulls in BBL beef-on-dairy (Bittante et al., 2018; Tagliapietra, Simonetto, & Schiavon, 2018). This can be explained by the hormonal regulation of fat and muscle deposition, where females and castrated males have a higher fat deposition compared with intact males (Zhang et al., 2010). The hormonal regulation also explains the smaller LT area found in heifers compared with bulls (Zhang et al., 2010).

4.2. *Meat quality of beef-on-dairy calves*

Previous studies on meat quality of crossbreeds reported that meat from ANG crossbreeds is darker (Keady et al., 2017), and has higher IMF% (Cafferky et al., 2019; Gagaoua et al., 2016; Keady et al., 2017; Keane & Moloney, 2009) compared with meat from BBL crossbreeds. Gagaoua et al. (2016) furthermore showed that CHA crossbreeds have higher IMF% than BBL crossbreeds, and Cafferky et al. (2019) saw the same trend. These findings are consistent with the findings in the present study, where the raw IMF% means for ANG × HOL, CHA × HOL, and DBL × HOL, with heifers and bulls pooled, are 3.52%, 2.99%, and 2.51%, respectively. These values differentiate the crossbreeds by approximately 0.5 percentage points and prove difference in meat quality between crossbreeds, with a large potential of ANG × HOL. This may be explained by the early maturity and the genetics of ANG.

Keady et al. (2017) and Cafferky et al. (2019) observed no differences between crossbreeds on cooking loss, which is consistent with our results. However, in constrast to our findings, the same was true for colour measurements. Furthermore, Cafferky et al. (2019) observed no differences between crossbreeds on WBSF, whereas Keady et al. (2017) observed a lower WBSF in ANG × Holstein-Friesian steers compared with BBL × Holstein-Friesian steers, which is in line with the well-established negative correlation between IMF% and WBSF (Cafferky et al., 2019; Hoa et al., 2023; Lee & Choi, 2019). This contradiction with our results can be explained partly by the higher slaughter age (app. 665 days) and partly by the longer ageing time of the meat (14 days) in the study by Keady et al. (2017). The small variation in WBSF and opposite relationship with IMF% in our study may be attributed to the short ageing time of 3 days, which has only allowed for limited proteolysis before analysis. In young animals, the impact of proteolysis is more important for WBSF than the contribution from IMF% (Therkildsen et al., 2020). According to Belew, Brooks, McKenna, and Savell (2003), the WBSF values in our study categorizes the meat as "tough" (> 45.11 N), which would most likely improve by further ageing (Hansen, Therkildsen, & Byrne, 2006).

When looking at previous research on meat quality of purebreds, some trends in our studies are confirmed. It has been reported that purebred ANG has darker meat, higher IMF%, and higher cooking loss than purebred BBL with no significant differences between breeds on pH and WBSF (Albrecht, Teuscher, Ender, & Wegner, 2006; Cuvelier et al., 2006). The same trend is seen in purebred ANG and CHA, where ANG has darker meat, higher IMF%, and higher WBSF than CHA, with no significant differences between breeds on pH (Christensen et al., 2011; Ripoll et al., 2018; Sinclair et al., 2001). Again, the higher WBSF and cooking loss in ANG could be explained by the age of the animals, as both studies investigated young bulls (Christensen et al., 2011; Cuvelier et al., 2006). Finally, it was shown that purebred CHA had higher IMF% than purebred BBL, with no significant differences between breeds on pH, cooking loss, colour traits or WBSF (Dufrasne et al., 2001). This relatively small difference between purebred CHA and BBL may be linked to the late maturity of both breeds, where ANG is an early maturing breed with more focus on IMF% in breeding programmes (Clarke et al., 2009; Mezgebo et al., 2017).

In terms of sex, meat from heifers generally exhibited higher meat quality than meat from bulls, where the raw IMF% means are 3.70% for heifers and 2.31% for bulls, with all crossbreeds pooled. This difference in IMF% of 1.4 percentage points underlines the potential for producing high-quality meat from heifers. In a previous study, Cafferky et al. (2019) compared bulls and steers of eight beef-on-dairy crossbreeds, three of them sired by ANG, CHA and BBL. They found that meat from steers had lower cooking loss, lower WBSF, and higher IMF%. In many aspects steers and heifers are comparable, as castration of bulls stops sexual maturation and induces hormonal changes, leading to reduced growth rates and increased fat deposition (Eichhorn, Bailey, & Blomquist, 1985; Pogorzelska-Przybyłek, Nogalski, Sobczuk-Szul, Purwin, & Kubiak, 2018). Acknowledging the similarity between heifers and steers, our results are consistent with the findings of Cafferky et al. (2019). In a broader perspective, previous research of other breeds reported that meat from heifers exhibited higher IMF% and lower WBSF scores, and in some cases also lower cooking loss, redder and lighter meat than meat from bulls (Bittante et al., 2018; Bureš & Bartoň, 2012; Hanzelkova, Simeonovova, Hampel, Dufek, & Subrt, 2011; Litwinczuk, Florek, & K, P., 2006; Pogorzelska-Przybyłek, Nogalski, Sobczuk-Szul, & Momot, 2021; Tagliapietra et al., 2018; Węglarz, 2010). These results align with our findings and with the well-established correlations between IMF%, which is negatively correlated with WBSF and cooking loss, and sometimes positively correlated with colour traits (Cafferky et al., 2019; Lee & Choi, 2019).

Overall, the values obtained from objective meat quality analyses are in alignment with previous findings on young ad libitum fed calves reporting pH_{48h} ranges 5.47–5.52, $L*_{48h}$ ranges 34.4–42.8, $a*_{48h}$ ranges 13.3–17.6, $b*_{48h}$ ranges 13.0–14.3, $WBSF_{48h}$ ranges 45.6–52.2 N, and IMF% ranges 0.65–3.96% (Bittante et al., 2018; Christensen et al., 2011; Cuvelier et al., 2006; Ripoll et al., 2018). The $L*$ and $a*$ values in our study are slightly higher, and the $b*$ values are slightly lower, and for all animals LT redness was higher than the consumer threshold value of 14.5 for acceptable beef colour (Holman, van de Ven, Mao, Coombs, & Hopkins, 2017).

4.3. Performance of Q-FOM™ Beef prediction model for intramuscular fat concentration

The Q-FOM was found to predict the IMF% concentration in LT from carcasses quartered at the 5th–6th thoracic vertebra with high accuracy and precision. Other studies have demonstrated good predictions of chemical IMF% from camera-based technologies in LT from carcasses quartered at 12th–13th rib (Pannier et al., 2023b; Stewart, Lauridsen, et al., 2021) and at 6th–7th thoracic vertebra (Kuchida et al., 2000). To some degree, the comparison of model performance between studies is challenging due to differences in the datasets used, especially R^2 varies with IMF% range. Kuchida et al. (2000) do not report RMSE values, but report $R^2 = 0.91$ for a dataset ranging from 2.1 to 27.1% IMF, similar to the model range of our study and with the same accuracy. More recently, Pannier et al. (2023b), reported good IMF% predictions by Marel conveyer vision scanner with high precision estimates of 1.16%, and high $R^2 = 0.87$ with model IMF% range 3.0–15.1%. Stewart, Lauridsen, et al. (2021) demonstrated high accuracy ($R^2 = 0.78$) and precision (RMSEP = 1.85%) of LT IMF% prediction by the prototype camera in carcasses quartered at the 12th–13th rib with a model IMF% range 1.5–18.6%.

Stewart, Gardner, et al. (2021) tested two prototype cameras, MIJ-mirror and MIJ-30, with relatively low accuracies ($R^2 = 0.4$ and $R^2 = 0.5$) despite the large model IMF% range (1.1–21.7% and 1.5–21.7%, respectively). However, the RMSECV values indicated a high precision of both camera models, with RMSECV = 1.5% and 1.6%, respectively. The variation in performance of the different models may be caused by the segmentation accuracy, as bone dust, fat particles, connective tissue, light reflectance of surface moisture, iridescence and variations in camera positioning may have led to misleading white pixels within pictures in many studies (Stewart, Gardner, et al., 2021). Furthermore, it should be stressed that IMF% is a three-dimensional trait that varies throughout LT, which complicates prediction of IMF% from a surface area (Pannier, van de Weijer, van der Steen, Kranenbarg, & Gardner, 2023a; Stewart, Gardner, et al., 2021).

As previously stated, the IMF% distribution and range of collected samples is affecting the accuracy values (R^2), as an increase in IMF% range potentially increases overall correlation (Pannier et al., 2023b). This may partly explain the relatively low correlation between the Q-FOM predicted IMF% and the chemical IMF% on the beef-on-dairy veal subsample representing a narrower chemical IMF% range from 0.9 to 7.4% ($R^2 = 0.48$, $RMSE_{veal} = 1.00\%$). Comparing the prediction error of the full model (RMSECV = 1.33%) with the IMF% standard deviation of the veal subsample (1.38%) shows that the resolution of prediction is comparable in size. This means that the variation in the reference data can barely be resolved by the Q-FOM IMF% model. Peña et al. (2013) also investigated prediction of IMF% in lean carcasses and found an unsatisfying performance (RMSE and R^2 not reported), where the model in many cases overestimated IMF%, although they tried to account for the IMF% variation within the muscle by taking pictures of both sides of the slice used for chemical IMF% analysis and using the average predicted IMF%. However, in the case of Q-FOM, binning of the veal subsamples in 2.5% IMF% intervals (three groups) still resulted in 62.6% of the carcasses being accurately predicted. This indicate that Q-FOM can provide valuable information on the IMF% content from a non-destructive and inexpensive measurement performed on the slaughter line. More importantly, the prediction model reveals relationships between beef-on-dairy groups (crossbreed and sex) similar to the relationships observed in chemical IMF% analyses. This reveals a potential for implementing Q-FOM at the grading station or in-chiller and utilizing these predictions in breeding programs, when aiming for higher meat quality in veal from beef-on-dairy. This would also enable the distinction between animals with higher IMF% and potentially affect beef market pricing based on meat quality via IMF% predictions.

5. Conclusions

Beef-on-dairy meat represent high-quality rosé veal with a low variation in pH. The study showed that DBL × HOL had excellent carcass characteristics with high slaughter weights, LT areas and EUROP conformation scores. On the other hand, ANG × HOL produced rosé veal of higher quality with darker meat and higher IMF%, but also higher WBSF. Differences between breeds in WBSF would likely be reduced or eliminated by further ageing. CHA × HOL exhibited intermediate performance between ANG × HOL and DBL × HOL for both carcass characteristics and meat quality. CHA represents a sire breed that matures relatively later and has the potential for achieving high meat quality. The same division was seen between sexes, where bulls performed better on carcass characteristics than heifers, and heifers produced meat of higher quality than bulls. These findings support the mismatch between the European payment system and the meat quality of the products. Q-FOM has the potential to breach this gap by offering an accurate and precise IMF% prediction model for carcasses quartered at 5th–6th thoracic vertebra. Beef-on-dairy veal crossbreeds could be differentiated based on their IMF% concentration and classification into three groups was achievable with 62.6% of the samples being allocated correctly. This reveals a potential of Q-FOM IMF% predictions to be used in breeding, when aiming for higher meat quality veal from beef-on-dairy.

Ethical statement

All animals used in this study were kept according to the Danish and European legislations for dairy and rosé veal production. Animal care and slaughter were performed in compliance with the European rules (Council Regulation (EC) No. 1/2005 and Council Regulation (EC) No. 1099/2009) on the protection of animals during transport and related operations, and at the time of slaughter, respectively. An ethics approval was not required for this study as data were collected on cuts intended for human consumption.

CRediT authorship contribution statement

Fie F. Drachmann: Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Mette Christensen:** Investigation, Methodology, Supervision, Writing – review & editing. **Jakob Esberg:** Formal analysis, Software, Writing – review & editing. **Thomas Lauridsen:** Conceptualization, Project administration, Resources. **Anders Fogh:** Conceptualization, Funding acquisition. **Jette F. Young:** Supervision, Writing – review & editing. **Margrethe Therkildsen:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Acknowledgements

This work was financially supported by the Graduate School of Technical Sciences (GSTS) at Aarhus University, Denmark, and as a part of the research project FutureBeefCross (J. 34009-18-1434), supported by the Green Development and Demonstration Programme (GUDP), Ministry of Food, Agriculture and Fisheries of Denmark. The authors thank the farmers and staff for delivering calves and feeding plans for FutureBeefCross. We thank Danish Crown for muscle sampling and Jens Askov Jensen, Department of Food Science, Aarhus University for his technical assistance with meat analyses.

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