Effects of breed-production system on collagen, textural and sensory traits of 10 European beef cattle breeds

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Short title: production system influenced beef collagen and texture

Abstract

In the current study the collagen, texture and sensory characteristics of meat from 712 yearling males of 10 local Spanish and French beef breeds raised in their typical production systems were described. The breed-production system affected collagen and texture variables but affected sensory variables only slightly. There was a large amount of intra-breed-production system variation for all the variables. French breeds had lower values for collagen solubility (approximately 12%) than Spanish breeds (approximately 40%). Stress (WB) varied from 36 N/cm^2 in Casina to 44 N/cm^2 in Salers, whereas compression stress at 80% ranged from 35 N/cm^2 in Asturiana de los Valles to 40 N/cm^2 in Salers. Oven cooking resulted in higher cooking losses (24%) than cooking on a grill (12%). Cooking losses increased as the grill temperature

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increased. Numerous significant correlations were found among variables. Carcass weight is associated with all the collagen and texture variables. Correlation coefficients among texture and collagen variables were statistically significant and these correlation coefficients were in general higher for solubility percentage than for total collagen content, highlighting the importance of the solubility of collagen rather than total collagen in determining meat textural properties.

Keywords: beef, breed, connective, sensory, texture.

Practical applications

To differentiate a product in the market, it is necessary to define its characteristics. Differentiation allows increasing the added value of products and, therefore, income of the farmers. In addition, it guarantees to the consumers that the product they purchase has the intrinsic and extrinsic quality features that they seek. For consumers, beef texture is one of the most important quality attributes sought, therefore studying factors that can affect beef texture is a major interest for the industry.

1. Introduction

Beef production is an important sector in the livestock industry in the European Union (EU). Local systems of beef production in the EU have a variety of characteristics, including several breeds, feeding systems and age or weight at slaughter. The current agricultural policy of the EU (https://europa.eu/european-union/topics/agriculture_en) aims to foster a new direction in the meat production industry, increasing the diversification of agricultural production and the promotion of specific products related to meat quality. In recent years, consumer perceptions of meat quality have changed, and consumers have become more interested in factors beyond sensory meat quality, that is, extrinsic qualities are becoming more important for consumers in developed countries (Brunso *et al.*, 2004; Verbeke *et al.*, 2010). In this sense, Chamorro et al. (2012) reported that consumers' purchasing decisions were based less on price, external appearance and origin and more on third-party certification of quality. In the context of EU, the main quality labels for meat or meat products are Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) Local and non-specialized beef breeds raised under traditional systems are usually covered under these EU labels, but also many other breeds have their own quality brands, such as Charolais, Limousine and Aberdeen Angus.

Meat quality characteristics are affected by various pre- and post-slaughter factors. Among them, the production system is of major importance, because a production system is essentially the combination of the animals' breed, sex, age, diet, environment and handling.

This study was a part of a large project examining several carcass and meat characteristics of 10 local Spanish and French beef breeds raised within their typical production systems.

Previous papers have described the carcass quality (Piedrafita *et al.*, 2003b) and some instrumental and sensory meat characteristics (Gil *et al.*, 2001b; Serra *et al.*, 2004a; Serra *et al.*, 2008a) of these breeds. Thus, the aim of the present study was to examine the texture, collagen and sensory variables of meat from animals that were raised in their respective breed-production systems.

2. Materials and methods

2.1. Animals

A total of 712 young bulls from ten breeds were used in this study: Asturiana de los Valles (AV, *n*=70), Bruna dels Pirineus (BP, *n*=67), Casina (CAS, *n*=70), Morucha (MO, *n*=70), Avileña-Negra Ibérica (NE, *n*=70), Pirenaica (PI, *n*=55), Retinta (RE, *n*=68), Aubrac (AU, *n*=78), Gasconne (GA, *n*=82) and Salers (SA, *n*=82). Young bulls were slaughtered locally at EU-licensed commercial abattoirs. Slaughter age ranged from 443 days of age to 552 days for Spanish breeds and from 610 days to 753 days for French breeds. The average slaughter weight was breed-specific, and depended on the degree of maturity and local market requirements Additional details regarding breed characteristics, growth, slaughter conditions and carcass traits are available in Piedrafita *et al.* (2003b).

2.2. Muscle sampling and analysis

Details about the meat sampling method can be found in Gil *et al.* (2001a), Serra *et al.* (2004a) and Serra *et al.* (2004b). Briefly, at 24 h post-mortem, the pH was measured on the *Longissimus thoracis* muscle at the 5th rib. Next, the *Longissimus thoracis* muscle from the 6th through 11th ribs was excised and the following variables were measured: concentration of the haem pigment (Hornsey, 1956), dry matter (ISO 1442), water holding capacity (Grau and Hamm, 1953), chemical intramuscular fat content (ISO 1443), crude protein quantification (ISO 937), determination of myosin heavy chain 1, lactate dehydrogenase (LDH) and isocitrate dehydrogenase (ICDH) activities and colour measurements.

Additionally, a 3.5-thick chop from the 8th rib was used for calculating the total and soluble collagen (Bonnet and Kopp, 1984). The sample for total collagen was immediately frozen, while the sample for the soluble collagen was first hydrolysed and then frozen (Kopp and Bonnet, 1982). The percentage of soluble collagen was calculated as the difference between the amount of total collagen and the amount of insoluble collagen left as a residue from the solubilization process. Since the collagen quantification method presents high inter-assay variability we carried out four repeated measurements by sample to increase measurements accuracy (Listrat and Hocquette, 2004).Next, a 3.5-cm-thick steak from the 9th rib was vacuum packed, kept at 4°C and aged for 14 days; thereafter, the steak was frozen at –18°C for texture analysis. For the texture analysis, the steaks were thawed inside their plastic bags in tap water for 4 hours until reaching an internal temperature of 15-17°C. Each steak was then cut transversally into two halves to be used in an analysis of either cooked or raw meat. For the cooked meat analysis, the meat was vacuum packed and cooked in a water bath at 75°C until the internal temperature reached 70°C. Temperature was monitored using a Jenway 2000 thermometer (Cole-Parmer, Staffordshire, UK). Stress (N/cm^2) and yield (N/cm^2) were recorded using a Warner-Bratzler (WB) device. The texture of the raw meat was analysed using a modified compression device that avoids transversal elongation of the sample (Lepetit and Culioli, 1994). For both the raw and cooked meat samples, a $1cm^2$ cross-section was cut with the muscles fibres parallel to the longitudinal axis of the sample. All texture measurements were taken using an Instron 4301 (Illinois Tool Works Inc., Norwood, Massachusetts, US). The stress was assessed when the device was no longer able to descend further, that is, when the sample had been compressed to its full height (i.e., maximum rate of compression), and at 20% and 80% of this maximum compression (N/cm^2).

For the sensory analysis, a 2-cm steak was sampled at the 10^{th}-11^{th} ribs. As in the texture analysis, samples were vacuum packed and kept at 4°C and aged for 14 days, then frozen and kept at –18°C. The freezing period was always less than 6 months. To assess the sensory characteristics, the samples were defrosted in tap water for 4 hours until they reached an internal temperature of 17-19°C. The samples were then analysed by teams in three different laboratories: Zaragoza (Spain) analysed AV, CAS, PI and RE; Monells (Spain) analysed NE, BP and MO; and Villers Bocage (France) analysed AU, GA and SA . The meat was cooked in aluminium foil on a double plate grill in Zaragoza and Villers Bocage and in an oven in Monells. The samples were cooked until they reached an internal temperature of 55°C in Villers Bocage and 70°C in Zaragoza and Monells. Then, each steak was trimmed of any external connective tissue, cut into 2-cm^2 samples, wrapped in labelled aluminium foil and stored for approximately 5 min at 60°C in warm pans until they were tasted. Samples were randomly served to trained ten-member sensory panels in Monells and Villers Bocage and to a trained eleven-member sensory panel in Zaragoza.Members of the panels were seated in individual booths under red lighting to mask differences in meat colour. The panellists assessed tenderness, juiciness, beef flavour intensity and overall appraisal using a non-structured ten-point scale. The experiment was carried out following a balanced design (ISO-8586). In addition, cooking losses were calculated as the difference in weight before and after cooking. More details for the panel in Monells are available in Serra *et al.* (2008a).

2.3. Statistical analysis

Animals in this experiment were raised in their typical production-systems, which have differences in slaughter age and maturity. Therefore, a generalized linear model (GLM) with breed-production system (denoted as breed hereafter) as a fixed effect and carcass weight as a covariate was used for the analyses of the collagen measures, texture variables and sensory variables. For the sensory variables and cooking losses, the GLM analysis was conducted for each laboratory separately, because the sensory analysis methodology was different at each laboratory. Least square means and standard errors were computed. Means were corrected for a carcass weight of 327.42 kg. Differences between breeds were assessed with significance based on Bonferroni adjustment to address multiple comparisons. Bivariate Pearson's correlation coefficient was calculated including texture variables, collagen variables and cooking losses with significance based on Bonferroni adjustment to address multiple comparisons. All analyses were performed with the SPSS 15.0 (SPSS Inc., Chicago, US).

3. Results

3.1. Summary of published results

Previous studies showed relevant differences in carcass and meat quality traits among the analysed breeds. According to those studies, all of the variables related to carcass and meat quality were affected by breed. The animals slaughtered in Spain weighed between 444 and 551 kg., whereas the animals slaughtered in France weighed between 610 and 750 kg. The daily weight gain ranged from 1.03 to 1.65 kg/day. Even across the wide range of carcass weights studied, the general relationships among carcass traits were confirmed. Animals with the best conformation were also leaner than less conformed animals, whereas long carcasses tended to be associated with poor conformation and fatness. Bone content was negatively correlated with carcass conformation and muscle content. RE and NE breeds were distinguished from the other breeds by their high intra-muscular fat content. The meat from non-specialized beef breeds was more oxidative. In terms of meat colour, AV, PI and NE had the palest meats, CAS and MO had the reddest and darkest meats, and BP had an intermediate colour. Meat colour was affected by the muscle biochemical traits since positive correlations between MHC-1 and haem pigment content were observed for most of the breeds, and haem pigment contents were correlated positively to a* and C* in most breeds.

3.2. Collagen and texture variables

Means, standard errors and p-values for the effect of breed on collagen and texture variables are presented in Table 1. A significant effect of the breed was observed for all the variables. In addition, all the measured variables showed a large amount of variation within breeds. The coefficient of variation for the total collagen content was 21% but variability for solubility percentage reached 48%. For variables related to texture, variability was 44% for stress, 47% for yield, 22% for compression load, 29% for compression at 20% and 23% for compression at 80%.

CAS and GA had lower values of total collagen than the rest of the breeds. Although GA and the other French breeds had the lowest values of collagen solubility (from 12.1% to 13.8%), CAS had high values for collagen solubility (40.9%). It was not statistically different from AV, PI, RE or BP. MO and NE had intermediate solubility percentage values (32.5%).

Stress varied from 36 N/cm^2 in CAS to 44 N/cm^2 in SA, whereas yield, which measures the limit of elasticity of the sample (Lepetit and Culioli, 1994), ranged from 22 N/cm^2 in SA to 46 N/cm^2 in AV. In the raw meat samples, compression stress was lower in BP and SA than in the rest of the breeds, whereas compression stress at 80% ranged from 35 N/cm^2 in AV to 40 N/cm^2 in SA.

3.3. Sensory variables

Table 2 shows the results of the GLM analyses completed by each laboratory for the sensory data. At the Villers Bocage laboratory, no significant differences were found in the sensory attributes among the French breeds ($p>0.05$). At the Zaragoza laboratory, only tenderness was influenced by the breed ($p=0.039$). At the Monells laboratory, all variables differed among breeds ($p<0.01$). Conversely, there was no significant breed effect on cooking losses in the Zaragoza laboratory nor in the Monells laboratory, whereas in the Villers Bocage laboratory, there were highly significant differences ($p<0.0001$) in cooking losses among the French breeds. Oven cooking resulted in greater cooking losses than grill cooking: meat cooked in an oven (BP, NE and MO breeds) had an average cooking loss of 24%, whereas meat cooked on a grill had average losses of only 8 and 14% when the internal temperature reached 70°C and 55°C, respectively. Variability in the data was similar for the Zaragoza and Monells laboratories (from 13 to 27%) and slightly lower for the Villers Bocage laboratory (from 8 to 19%).

3.4. Pearson Correlations

There were some significant correlations between collagen and texture variables (Table 3). Carcass weight influenced all of the variables, and because of that, carcass weight was included as a covariate in the models. The percentage of soluble collagen had a stronger correlation with textural variables than the total collagen content, which highlights that collagen solubility, rather than the total amount of collagen, is important in defining the textural quality of meat. The Warner-Bratzler test variables were closely correlated, and the compression variables were closely correlated, but weak relationships were observed between the Warner-Bratzler and the compression test variables.

4. Discussion

4.1. Collagen and texture variables

The total collagen content values reported herein were similar to those reported by Campo *et al.* (2000b) in several Spanish breeds (from 2.3 mg/g to 4.7 mg/g), and by Christensen *et al.* (2011b) in several European breeds (approximately 3.5 mg/g). The breed effect on collagen characteristics agrees with previous studies completed by several authors (Jeremiah and Martin, 1982; Campo *et al.*, 2000b; Christensen *et al.*, 2011a). Differences in the production systems may explain breed-specific differences in these other studies. In central and northern Europe, cattle feeding is based on grazing in natural pastures that are supplemented with concentrate and/or high quality forage (silage, hay) at the end of fattening period. Alternatively, in the European Mediterranean regions, cattle are primarily raised on concentrate ad libitum and cereal straw throughout the fattening period. Feed with higher energy value was related to decreased total collagen content because of the higher protein deposition diluting the collagen content (Archile-Contreras *et al.*, 2010). It should be noted that the slaughter criterion used in this study was the degree of maturity, which implies differences in the chronological age at slaughter (Piedrafita *et al.*, 2003a), because animals were raised in their typical production system. Blanco *et al.* (2011) reported that the relationship between collagen content and age follows a quadratic relationship, where collagen content is higher at birth and at puberty than during the growing period.

Our solubility percentage values were higher than those found by other authors in several European breeds (Seideman, 1986; Christensen *et al.*, 2005; Christensen *et al.*, 2011b; Moran *et al.*, 2017) but similar to those reported by Campo *et al.* (2000c) and Panea *et al.* (1999) in Spanish breeds. French breeds had much lower collagen solubility than the rest of the breeds. Schreurs *et al.* (2008) published a meta-analysis including 33 different experiments carried out in French breeds and found an average solubility percentage of 19.35%, but they reported values of 12.8% and 12.7% in the Aubrac and Salers breeds, respectively. However, the effect of the solubilization method on the solubility percentage should be considered when comparing these studies, as it is widely accepted that the duration and temperature of the solubilization method affect the results (Kopp, 1971). Many authors use a 77°/75 min procedure (Crouse *et al.*, 1985; Seideman, 1986), while we used a 90°/2 hours procedure, following the method described by Bonnet and Kopp (1984). Alternatively, the percentage of soluble collagen also depends on the pH of Ringer’s solutions (Latorre *et al.*, 2016) and solubility is higher at when the pH of Ringer’s solution is 5.6 than when the pH of Ringer's solution it is 7.4. The pH of the solution used in the current project was 7.5. Finally, there would be an overestimation of collagen solubility when the samples are solubilized before freezing (Jeremiah and Martin, 1982).

Kopp (1971) stated that collagen solubility in males reaches its maximum at 13 months of age and subsequently decreases until the animals reach 19 months of age. This fact could partly explain the differences between the Spanish and French breeds because the French animals were older at slaughter. Additionally, as the age of the animal increases, collagen forms thermally stable, mature crosslinks that cause a decrease in collagen solubility (Judge and Aberle, 1982; Horgan *et al.*, 1991; Bosselmann *et al.*, 1995). Some discussions can be found in the literature concerning diet effects on collagen solubility. One study found that high-energy diets promoted the turnover of newly synthesized soluble collagen (Therkildsen *et al.*, 2011), while Archile-Contreras *et al.* (2010) reported that heat-soluble collagen was lower in corn-fed cattle than in cattle finished on alfalfa pasture. Cox *et al.* (2006) concluded that the finishing diet (grain vs. forage) did not affect insoluble or soluble collagen. Additionally, Damergi *et al.* (1998) suggested that daily weight gain was an important factor in determining collagen characteristics. As explained, we worked with animals which differed in age at maturity, since every breed was raised within their typical production systems. As a consequence, slaughter ages ranged from 364 days to 541 days in Spanish breeds and from 61 days to 753 days in French breeds. Therefore, our results suggest that collagen solubility might be the best parameter for detecting differences among breed types when the animals are of similar age. Alternatively, different breeds could be at different maturity stages at the same or similar chronological age and this could influence the crosslinking degree of the collagen (Kopp, 1971; Damergi *et al.*, 1998). Consequently, these differences in maturity may partially explain variation in the thermal properties of intramuscular collagen.

All the texture variables were similar to those reported in the literature for animals of similar characteristics (Campo *et al.*, 1999; Campo *et al.*, 2000a; Macíe *et al.*, 2000; Monsón *et al.*, 2003; Monson *et al.*, 2004; Oliván *et al.*, 2004; Sanudo *et al.*, 2004; Olleta *et al.*, 2005; Panea *et al.*, 2010a; Christensen *et al.*, 2011a; Panea *et al.*, 2011; Barahona *et al.*, 2016). Some authors reported a lack of breed or production system effect on texture variables (Vieira *et al.*, 2006; Marino *et al.*, 2011; Guerrero *et al.*, 2013), whereas other authors found such an effect (Sañudo *et al.*, 2004; Christensen *et al.*, 2011b; Panea *et al.*, 2016). Campo *et al.* (2000b) suggested that the meat textural characteristics were defined by breed purpose, but in the present study, the textural characteristics did not follow a clear pattern in the ten European breeds we tested. Two non-specialized breeds, Casina and Avileña, had the lowest values for stress, and they were not different from the Bruna or PI breeds, two breeds raised specifically for meat. In addition, the French breeds had the lowest values for yield, but the Salers breed, a hardy breed, had the same values for stress as the Asturiana, a double-muscled breed. We expected that yield, which measures the limit of elasticity of the sample, would be related to connective tissue, but the relationship was not significant (Table 3).

4.2. Sensory variables and cooking losses

The sensory attributes of the analysed breeds fell within the range described by most authors (Campo et al., 1998; Campo et al., 1999; Ciria et al., 2000; Gorraiz et al., 2002; Olleta et al., 2006; Serra et al., 2008a; Serra et al., 2008b; Panea et al., 2011; Guerrero et al., 2013; Gagaoua et al., 2016). In the literature, there is not a clear consensus about a breed effect on the sensory quality of meat. Campo et al. (1999) reported that sensory variables are influenced by breed purpose, whereas Panea (2002) did not find differences in tenderness, juiciness or overall appraisal of the meat from several European breeds whose meat was aged for 14 days. Similarly, Monson et al. (2005) found no significant differences in odour intensity in the meat from Spanish Holstein, Parda de Montaña, Limousin and Blonde d'Aquitaine breeds whose meat was aged for different lengths of time. Consequently, Monson et al. (2005) concluded that longer ageing times reduced between-breed variability in sensory variables. In the current experiment, the meat was aged for 14 days.

Comparison between laboratories are difficult in sensory analysis. Gagaoua et al. (2016) in an inter- laboratory study with different types of animals and two endpoint temperatures, found that tenderness and juiciness scores were lower at the higher internal end-point cooking temperature, independent of the sensory protocol used whereas the endpoint temperature effect on beef flavour depended on lab conditions. Nevertheless, in the current experiment, inter-laboratory comparison was not possible because each laboratory worked only at one endpoint temperature.

The cooking losses we found were similar to those reported by other authors in breeds with similar characteristics (Panea, 2002; Panea *et al.*, 2010a; Panea *et al.*, 2011). Cooking losses are important because they explain part of the variation in juiciness and because they influence meat appearance (Aaslyng *et al.*, 2003). Significant differences in cooking losses were observed between the three French breeds sampled. Conversely, there were no significant differences in cooking losses among the Spanish breeds, which agrees with the absence of a breed effect on cooking losses described by several authors (Panea, 2002; Aviles *et al.*, 2015). In this study, the cooking method influenced cooking losses. Panea *et al.* (2008) reported that cooking losses were greater for grilling than for a water bath. When examining four different cooking methods, Turp (2016) reported a significant effect of cooking method on meatball cooking losses. Pathare and Roskilly (2016) provided a good review of the influence of the cooking method and temperature on cooking losses. It is well known that different cooking techniques, the duration of cooking and core temperatures have a large effect on the physical properties of the meat and its eating quality (Combes *et al.*, 2003). Temperature influences the rate and extent of changes in protein structure, whereas the method of heat transfer (air, steam or contact) affects sensory perception (Bejerholm and Aaslyng, 2003). The changes that occur during cooking affect both the myofibrillar and connective tissues: heat solubilizes collagen, which causes tenderization of the meat but also denatures the myofibrillar proteins, resulting in an increase in toughness of the meat (Obuz *et al.*, 2003).

4.3. Pearson's Correlations

High correlation coefficients were detected among the Warner-Bratzler variables and among the compression variables, as has been described in the literature (Ngapo *et al.*, 2002; Panea *et al.*, 2010a). It is common to find a lack of correlations between the Warner-Bratzler and compression variables, as we observed in this study. As noted by Panea *et al.* (2010b), this absence of correlations is commonly due to differences in the sample preparation, since the Warner-Bratzler test is usually carried out with cooked meat, whereas the compression test is usually carried out with raw meat. Panea *et al.* (2010b) demonstrated that the Warner-Bratzler variables were highly correlated with the compression test variables when the samples were prepared in the same manner. It was reported that the amount and properties of collagen are important factors in determining the toughness of the meat (Cross *et al.*, 1973) but the significance of the collagen influence on texture variables differs among studies. For example, Torrescano *et al.* (2003) in a study with several muscles reported high correlation coefficients between the Warner-Bratzler variables and collagen content and solubility. Alternatively, Chriki *et al.* (2013) in a meta-analysis including several muscles of more than 500 animals reported that WB shear was significantly correlated with insoluble collagen amount but not with total collagen content. On the other hand, Christensen *et al.* (2011b)reported that total and insoluble collagen content were significantly correlated with compression variables measured in raw but not with WB shear independently of whether the meat was raw or cooked. In general, when samples used in the analysis had marked differences in collagen amount or solubility, significant correlations were found. However, when samples had low collagen content (Dransfield, 1977), as m. *Longissimus thoracis et lumbroum* (Listrat and Hocquette, 2004), no significant correlation was found. This would explain the lack of significance in the current study.

5. Conclusions

From the current results, it can be concluded that the breed-production system is an important factor contributing to the variation in both collagen and meat texture traits, whereas sensory characteristics are less affected by the breed. All the variables examined had high within-breed variability. These results suggest that collagen solubility might be the best parameter to use for detecting differences among breeds when the animals are of similar age and that differences in age at maturity are essential for explaining the thermal properties of intramuscular collagen. Despite an effect of the breed-production system on the texture variables, it was not possible to detect a relationship between the texture variables and breed-aptitude or chronological age. The cooking method affected cooking losses, with oven cooking resulting in greater cooking losses than grill cooking. As the temperature of the grill increased, the cooking losses also increased. Because collagen, texture and sensory variables varied as a function of carcass weight, including carcass weight in the models as a covariate is recommended to accurately compare meat traits that may depend on carcass weight. The percentage of collagen solubility was more strongly correlated with texture and sensory variables than total collagen content, which highlights that solubility, rather than the total amount of collagen, is important in defining meat textural and sensory quality. All Warner-Bratzler test variables were closely correlated, as were the compression variables, but there were only weak relationships between Warner-Bratzler and compression test variables. Weak or no correlations were found between the collagen and texture variables. All of the sensory variables were closely related to each other.

Ethical Statements

The authors declare that they do not have any conflict of interest. All procedures were approved by the animal experimentation ethics committee of the Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA). Written informed consent was obtained from all study participants.

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Table 1. Least square means, standard errors (s.e.) and p-values for the effect of breed-production system on collagen and texture variables in ten local European beef cattle breed-production systems.

	CAS	AV	NE	BP	MO	PI	RE	AU	GA	SA	s.e.	P-value
Total collagen (mg/g)	2.47 ^{b}	2.94 ^{a}	3.39 ^{a}	3.15 ^{a}	2.73 ^{a}	2.90 ^{a}	3.06 ^{a}	2.86 ^{a}	2.56 ^{b}	3.12 ^{a}	0.025	≤0.0001
Collagen solubility (%)	40.90 ^{a}	42.36 ^{a}	32.50 ^{b}	39.43 ^{a}	32.56 ^{b}	40.33 ^{a}	39.94 ^{a}	13.26 ^{c}	13.78 ^{c}	12.16 ^{c}	0.395	≤0.0001
Stress Warner-Bratzler (N/cm^2)	35.98 ^{c}	41.39 ^{ab}	36.87 ^{c}	39.42 ^{bc}	43.94 ^{ab}	38.10 ^{bc}	41.53 ^{ab}	37.43 ^{bc}	38.82 ^{bc}	44.29 ^{a}	0.488	≤0.0001
Yield Warner-Bratzler (N/cm^2)	37.93 ^{bc}	45.51 ^{a}	37.72 ^{bc}	41.85 ^{ab}	44.46 ^{a}	38.13 ^{bc}	44.92 ^{a}	21.84 ^{d}	34.03 ^{c}	21.60 ^{d}	0.624	≤0.0001
Compression load (N/cm^2)	62.86 ^{abc}	56.37 ^{d}	62.50 ^{abc}	58.82 ^{cd}	59.39 ^{bcd}	56.24 ^{d}	58.23 ^{cd}	68.37 ^{ab}	64.58 ^{abc}	69.07 ^{a}	0.600	≤0.0001
Compression stress at 20% (N/cm^2)	5.24 ^{a}	4.95 ^{a}	5.04 ^{a}	4.18 ^{b}	4.83 ^{a}	5.12 ^{a}	4.59 ^{a}	4.34 ^{a}	4.98 ^{a}	3.81 ^{b}	0.057	≤0.0001
Compression stress at 80% (N/cm^2)	38.77 ^{a}	34.59 ^{b}	38.41 ^{a}	37.35 ^{a}	34.90 ^{b}	35.50 ^{b}	35.82 ^{a}	39.85 ^{a}	35.41 ^{b}	40.18 ^{a}	0.362	0.002

CAS- Asturiana de las Montañas, AV- Asturiana de los Valles, PI- Pirenaica, RE- Retinta, BP- Bruna dels Pirineus, MO- Morucha, NE- Avileña-Negra Ibérica, AU- Aubrac, GA- Gasconne, SA- Salers. Different superscripts in the same row indicate statistically significant differences ($p<0.05$) among breeds. Corrected carcass weight = 327.42 kg.

Table 2. Least square means, standard errors (s.e.) and p-values for the effect of breed-production system on sensory variables in ten local European beef cattle breed-production systems. Generalized linear models (GLM) were completed independently for each laboratory.

Laboratory	Zaragoza						Monells					Villers Bocage				
Cooking method	Grill						Oven					Grill				
Cooking temperature	70°C						70°C					55°C				
Breed	CAS	AV	PI	RE	P-value	s.e.	BP	NE	MO	P-value	s.e.	AU	GA	SA	P-value	s.e.
Tenderness	6.12 ^{ab}	6.03 ^{b}	6.54 ^{a}	6.01 ^{ab}	0.039	0.062	4.56 ^{a}	5.35 ^{b}	4.69 ^{a}	≤0.0001	0.054	5.93	6.49	6.17	0.163	0.065
Juiciness	4.92	5.18	4.92	5.14	0.360	0.065	4.37 ^{ab}	4.43 ^{b}	3.99 ^{a}	0.003	0.053	6.25	6.15	6.20	0.856	0.037
Beef flavour	5.33	5.37	5.20	5.30	0.464	0.038	4.50 ^{a}	5.07 ^{b}	5.01 ^{b}	0.008	0.042	6.23	6.17	6.20	0.911	0.032
Overall appraisal	4.62	4.57	4.37	4.68	0.341	0.052	4.69 ^{a}	5.38 ^{b}	4.87 ^{a}	≤0.0001	0.044	6.01	6.31	6.19	0.630	0.050
Cooking losses	14.39	14.33	15.18	13.53	0.176	0.240	23.61	23.26	24.13	0.683	0.396	8.27 ^{b}	9.78 ^{a}	7.36 ^{c}	≤0.0001	0.090

CAS- Asturiana de las Montañas, AV- Asturiana de los Valles, PI- Pirenaica, RE- Retinta, BP- Bruna dels Pirineus, MO- Morucha, NE- Avileña-Negra Ibérica, AU- Aubrac, GA- Gasconne, SA- Salers. Different superscripts in the same row indicate statistically significant differences ($p<0.05$) among breeds within each laboratory.

Table 3. Pearson bivariate correlation coefficients for texture variables, collagen variables and cooking losses in ten local European beef cattle breed-production systems. Only significant coefficients are shown. Correlation coefficients that were significant at $p<0.05$ are shown in italics, all other correlation coefficients were significant at $p<0.01$.

	Total collagen	Solubility percentage	Stress WB	Yield WB	Comp. load	Comp. 20%	Comp. 80%	Cooking looses
Carcass weight	-0.126	-0.621		-0.437	0.099	0.309	-0.007	-0.577
Total collagen		0.242				-0.127	0.139	0.159
Solubility percentage				0.377	-0.169	-0.174		0.406
Stress WB				0.605		0.166	-.092	
Yield WB					*-0.088*			0.312
Compression load						0.205	0.677	*-0.098*
Compression 20%							0.276	-0.188