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Non-destructive determination of fat content in green hams using ultrasound and X-Rays

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ABSTRACT

This work addresses the use of ultrasound (US) and medical dual energy X-ray absorptiometry methods to predict the fat content in green pork hams. Ultrasonic velocity (υ) and X-Ray absorption were measured in 78 green hams. An increase in the fat content involved an increase in υ and a decrease in the X-Ray attenuation measured at 2 ºC. Models developed to predict the fat content from the ultrasonic velocity or X-Ray parameters provided errors of 2.97% and 4.65%, respectively. The combination of both US and X-Ray technologies did not improve prediction accuracy. These models allowed green hams to be classification into three levels of fatness, with 88.5% and 65.4% of the hams correctly classified when using models based on ultrasonic and X-Ray parameters, respectively. Therefore, US and X-Rays emerge as useful quality control technologies with which to estimate the fat content in green pork hams.

Keywords: Non-destructive analysis; Green ham; Meat products; Ultrasound; X-Rays

1. INTRODUCTION

The total fat content of green hams is a key issue, since it affects the processing of both cooked and dry-cured hams. In cooked hams, intramuscular fat can affect the binding strength and consumer acceptability. In dry-cured hams, the fat content has a great influence on the salt uptake during the salting process (Cierach, & Modzelewska-Kapitula, 2011) and on the weight losses during drying (Čandek-Potokar, & Škrlep, 2012; Garcia-Gil et al., 2012). The development of online non-invasive technologies as a means of predicting the fat content in green hams is of special interest for the meat industry, since they would make it possible to classify the product into different fat categories which would allow the elaboration processes to be optimized. These techniques need to be robust and cost-effective for being used in the industry.

New techniques are being tested for carrying out the non-destructive determination of the composition of the meat products. For live animals and carcass inspection, reliable ultrasonic devices are available for the measurement of lean and fat content (Miles, Fisher, Fursey, & Page, 1987; Miles, Fursey, Page & Fisher, 1990), as well as the depth of subcutaneous fat, in particular sites of the animal. Miles & Fursey (1977) related the ultrasonic velocity to the fat content of meat muscles, comminuted tissue, meat mixtures and dehydrated muscles. In this regard, Koch et al. (2011a) estimated the intramuscular fat content of porcine *Longissimus dorsi* muscle by using ultrasound velocity and attenuation. Corona, García-Pérez, Ventanas, and Benedito (2014) and Benedito, Carcel, Rosello, and Mulet (2001) have also used ultrasound to determine the composition of a formulated dry-cured pork meat product (sausage) and raw pork meat mixtures, respectively. Most of the aforementioned ultrasonic studies rely on the measurement of the ultrasonic velocity, because it is the simplest and most reliable ultrasonic measurement. However, each ultrasonic measurement provides information on a reduced area of the sample which implies that, if large samples are to be analyzed, multiple measurements are required. Moreover, the results are largely dependent on the temperature and anisotropy of meat tissues (Miles & Fursey, 1977). In this regard, other non-destructive techniques, such as X-Rays, do not require a precise temperature control.

There are several X-Ray technologies that, based on the differential X-Ray attenuation produced by the different tissue density, permit meat composition to be determined. X-Ray computed tomography has been used to predict the lean/fat content in animal carcasses (Vester-Christensen et al., 2009) and bone-in green hams (Picouet, Muñoz, Fulladosa, Daumas, & Gou, 2014) and to determine the intramuscular fat content of meat (Font-i-Furnols, Brun, Tous, & Gispert, 2013). Brienne, Denoyelle, Baussart, and Daudin (2001) used Medical Dual Energy X-Ray Absorptiometry (DEXA) to predict the fat content in pork meat/fat mixtures and beef muscles. Although a low correlation was observed between the percentage of fat obtained through chemical analyses and the percentage estimated from the Beer-Lambert equation, they proposed different corrections and obtained an improvement. However, corrections are specific for each sample format and DEXA equipment. Mercier et al. (2006) used the ratio between the coefficients of attenuation of the two X-Ray energy levels obtained with a medical DEXA to predict the fat content in legs of lamb carcasses. The predictions underestimated the fat content, probably because dissected fat was used instead of chemically analyzed fat for predictive model development. López-Campos, Larsen, Prieto, Juárez, and Aalhus (2013) reported that DEXA technology may also be useful for the objective estimation of the intramuscular fat content in beef. Nevertheless, the medical devices used in the aforementioned studies are not suitable for working in industrial environments at the required speed. In this sense, other authors demonstrated that non-medical X-Ray instruments also allow the online determination of the salt uptake in whole bone-in hams during the salting procedure (Fulladosa, Muñoz, Serra, Arnau, & Gou, 2014) and the accurate estimation of the fat content of boned and packaged meat trimmings (Hansen et al., 2003).

Nevertheless, more research is needed before using ultrasound and DEXA technologies to determine the composition of products in which the fat is not uniformly distributed or that contain bones. Fat content determination in whole pieces, such as green bone-in hams, is still a challenge because among others the presence of bones and the existence of different muscles with a high degree of heterogeneity in terms of their fat content and distribution. Besides, combining the information obtained from acoustic and electromagnetic waves as a means of achieving more accurate predictions is worth investigating. Thus, the aim of the present study was to analyze the ability of ultrasound and DEXA techniques to predict both separately and jointly the fat content of green hams and to determine the feasibility of using them for industrial classification purposes.

2. MATERIAL AND METHODS

2.1 SAMPLES

Thirty nine green hams from ‘White’ pigs (crosses containing Duroc (CDU) or Large White (CLW)), average weight 11.1±0.8 kg, and 39 green hams from ‘Iberian’ pigs (crosses containing at least 50% Iberian breed (CIB)), average weight 10.6±1.2 kg, were purchased in 2 different slaughterhouses. The hams were taken to the pilot plant in refrigerated storage and kept at 2±2 ºC for less than 2 days before the non-destructive measurements were conducted. The different genetic source of the hams allowed for a wide range of fat contents.

2.2 ULTRASONIC MEASUREMENTS

A specific device was designed and assembled for ultrasonic measurements; it mainly consisted of a couple of narrow-band ultrasonic transducers (1 MHz, 0.75'' crystal diameter, A314S-SU model, Panametrics, Waltham, MA, USA), a pulser-receiver (Model 5058PR, Panametrics, Waltham, MA, USA) and a digital oscilloscope (Tektronix, TDS5034, Digital phosphor oscilloscope. Tektronix inc. Bearverton, OR, USA). A digital height (192-633 Serie, Mitutoyo, Japan) gage was linked to the computer by a RS 232 interface in order to measure the sample thickness (±0.01 mm) (Figure 1A).

The ultrasonic velocity was calculated from the time of flight (an average of 3 signal acquisitions) and the sample thickness. In order to assess the ultrasonic velocity, the system delay was taken into account, which was determined from the pulse transit time measured across a set of methacrylate cylinders of different thicknesses. The delay time was then obtained from the intercept on the y-axis of the time versus thickness graph.

The ultrasonic measurements were taken in three zones of the ham (FC, BE and C), as shown in Figure 1A. The number of experimental measurements carried out in each zone depended on the hams' surface and weight. On average, 20 measurements were carried out in the cushion (C) and 5 in the fore cushion (FC) and butt end (BE). Measurements were carried out in triplicate. The hams were kept at 2±2 ºC for 24 hours before the ultrasonic velocity was measured in place. The ultrasonic velocity in the ham was calculated as the average of the 30 ultrasonic velocities measured in all the ham zones. The average ultrasonic velocity was correlated to the fat content of the green hams.

2.3 X-RAY ABSORPTIOMETRY MEASUREMENTS

A commercially available X-Ray inspector model X20V G90 (Multiscan technologies, S.L, Cocentaina, Spain) was used to scan the samples at 2 ºC. X-Rays were emitted from below the samples and the transmitted X-Rays were measured in the upper part of the equipment while a conveyor belt moves the sample through at 0.33 m s^{-1} (Figure 1B). The device uses low-energy X-Rays to obtain images (matrixes of values, 4000 x 1280 pixels) of the scanned object in the horizontal plane. Samples were scanned at three different voltages and intensities, specifically 90 kV and 4 mA, 70 kV and 8 mA and 50 kV and 15 mA, in exactly the same position and location in order to combine the information obtained from the three matrixes of values. Matrixes of attenuation values were imported and analyzed using a specific Matlab code (MATLAB, Ver. 7.7.0, The Mathworks Inc., Natick, MA, USA).

The global X-Ray attenuation value (A) for each sample and used energy was obtained by the following equation:

$$A = -Ln \cdot \frac{\sum I_{(i;j)}}{\sum I_{0(i;j)}} \quad \text{(Eq. 1)}$$

Where I is the of the radiation transmitted through each pixel of the matrix $(i;j)$; I_0 is the energy of the incident radiation to each pixel of the matrix $(i;j)$; i ranges from 1 to 4000 and j ranges from 1 to 1280. Therefore, attenuation values for measurements carried out at 50, 70 and 90 kV were obtained (A_{50}, A_{70} and A_{90}).

According to the Beer-Lambert law, X-Ray attenuation is proportional to the thickness and composition of the sample (n components):

$$A = L \cdot \sum_{i=1}^{n} \varepsilon_i \cdot c_i = \frac{L}{V} \cdot \sum_{i=1}^{n} \varepsilon_i \cdot M_i \quad \text{(Eq. 2)}$$

Where L is the sample thickness (m), V is the sample volume (m^3), ε_i is the absorptivity coefficient of component i (m^2 kg^{-1}), which is dependent on the X-Ray energy, and c_i and M_i are the concentration (kg m^{-3}) and the mass (kg) of absorbing component i, respectively.

Eq (2) can be converted into Eq (3) by dividing by the ham weight (M_t):

$$\frac{A \cdot V}{L \cdot M_t} = \sum_{i=1}^{n} \varepsilon_i \cdot X_i \quad \text{(Eq. 3)}$$

Where Xi is the mass fraction of component i.

Since hams do not have a uniform thickness, an average thickness was estimated as the ratio between V and the sample surface in the scan (S). Then, a new parameter (A_T) can be calculated from Eq. (3):

$$A_T = \frac{A \cdot S}{M_t} = \sum_{i=1}^{n} \varepsilon_i \cdot X_i \quad \text{(Eq. 4)}$$

The correlation between A_T, obtained at different voltages (A_{T50}, A_{T70} and A_{T90}), with the fat content was analyzed.

2.4 DISSECTION AND CHEMICAL ANALYSIS

After the ultrasound and X-Ray measurements, the lean and fat tissues for each ham were dissected, weighed and minced together. Afterwards, the fat and moisture contents of the mixture were determined. The moisture was analyzed by drying at 103±2 ºC until reaching constant weight (ISO 1442, 1997). The total fat content was estimated by near infrared spectroscopy using a FoodScanTM Lab (Foss Analytical, Dinamarca) according to AOAC (2007). All analyses were performed in triplicate. The fat (X_f) and moisture (X_w) contents of the whole hams were calculated by referring the mixture composition to the ham weight.

2.5 DEVELOPMENT OF PREDICTIVE MODELS AND STATISTICAL ANALYSIS

The green hams used in this study were split into two sets. The first set (Model Calibration, MC) included 52 hams and was used to develop predictive models using ultrasonic and X-Ray absorptiometry parameters. The rest of the hams (26) were used for model validation (MV set). In order to cover a wide range of fat content in each set of hams (Table 1), they were sorted according to the experimental fat content and for each group of 3 hams, 2 hams were systematically included in the MC set and 1 in the MV set. In addition, the hams of the MV set were divided into 3 groups according to their fat content (low<14%, medium 14-26% and high>26% fat content level).

Predictive models were established to find single and multiple regression models between the fat content and the ultrasonic and X-Ray variables. For that purpose, the XLSTAT 2009 statistical package (Microsoft Office, Redmond, WA, USA) was used. Regarding the ultrasonic measurements, only the ultrasonic velocity (υ) was used because other variables, such as attenuation and the frequency spectrum analysis, did not provide relevant information. For X-Ray measurements, A_T values obtained at different energies were used. The combination of US and X-Ray parameters was also investigated. In this case, the independent variables of the model were selected by the Stepwise method, the levels of significance to enter and keep the dependent variables in the model being p=0.05 and p=0.1, respectively. The reliability of the predictive models was given by the coefficient of determination (R^2) and the Root Mean Square

Error of Calibration (RMSEC). For the validation data set, the Root Mean Square Error of Validation (RMSEV) was also calculated.

3. RESULTS AND DISCUSSION

3.1 CHEMICAL COMPOSITION

The chemical composition of the green hams used in this study is shown in Table 1. The fat and moisture content ranged between 6.5-41.0% w.b. and 39.9-70.2% w.b., respectively. These ranges of fat and moisture contents cover the fat and moisture contents of the majority of hams usually found on the market (Serra, & Fulladosa, 2011; Blasco et al., 1994).

3.2 INFLUENCE OF FAT ON ULTRASONIC VELOCITY

Figure 2 (A and B) shows the relationship between the ultrasonic velocity (υ) and the fat (X_f) and moisture contents (X_w) in the 78 green hams analyzed. It should be highlighted that the υ reported in each point of Figure 2 is the average ultrasonic velocity of a whole ham (30 measurements distributed in the three zones, Figure 1A), as explained in section 2.2. There is great experimental variation in the ultrasonic response to differences in moisture and fat content, which is especially noticeable for fat contents between 20 and 28% w.b. (Figure 2). This general variability could be linked to the highly heterogeneous nature of the ham, which is a piece made up of subcutaneous fat and different muscles, also containing a heterogeneous distribution of intramuscular fat and connective tissue. In addition, the breed of the pig and feeding system could significantly modify the υ in the fatty fraction and affect the protein content in the lean tissue, which would also determine the υ in the muscles (Niñoles, Mulet, Ventanas, & Benedito, 2011; Niñoles, Sanjuan, Ventanas, & Benedito, 2008).

As can be observed in Figure 2A, an increase in the fat content involved an increase in the υ measured at 2 ºC. Thus, on average, an increase in the fat content of 5% corresponded to an increase of 8.4 m s^{-1} in the υ. This result is explained by considering that, at low temperatures, the ultrasonic velocity in the fatty tissue is higher than in lean tissue. This fact has been previously reported by Benedito et al. (2001), who found an ultrasonic velocity of 1610.0-1620.0 m s^{-1} in fatty pork tissues and 1530.0-1555.0 m s^{-1} in lean pork tissues at 4 ºC. Similarly, Miles & Fursey (1977) reported ultrasonic velocities at 4 ºC in intact beef muscles of around 1530 m/s and significantly higher (1650 m/s) for beef adipose tissue. The ultrasonic velocity in fatty tissue is so high at this temperature because it depends on the solid/liquid ratio which affects its textural properties; consequently, as the state of the fat at low temperatures is mainly solid, in which ultrasound propagates faster, the υ reaches its highest values. In contrast, the ultrasonic velocity in lean tissue is lower because the main component in raw meat is water and the ultrasonic velocity in water at 2 ºC is 1412.8 m s^{-1} (Kinsler, Frey, Coppens, & Sanders, 1982). The ultrasonic velocity in the whole ham is lower (1531.1-1586.9 m s^{-1}, Figure 2A) than in the fatty tissue because it is greatly influenced by the water content of the lean tissue.

It should be emphasized that the influence of the fat content on the υ in ham is highly temperature dependent. In this regard, the υ in pure fat decreases with the rise in temperature (McClements, & Povey, 1992). This fact has also been observed in different meat products, where velocity was measured at between 2 and 38 ºC (Corona et al., 2014; Koch et al., 2011b; Niñoles et al., 2008; Chanamai, & Mc.Clements, 1999), the reduction in velocity being mainly ascribed to the fat melting as the temperature rises. The temperature used (2 ºC) is appropriate for fat content assessment, since there is a remarkable difference between the υ in the fatty and lean tissues. As the temperature increases, the ultrasonic velocity in fat falls and that of lean tissue goes up, leading to similar υ values for both tissues, which hinders the fat content estimation.

The moisture content was found to have the opposite effect on υ to that reported in the case of fat (Figure 2B). Thus, in average terms, an increase in the moisture content of the green ham of 5% corresponded to a decrease of 9.6 m s^{-1} in υ. As previously mentioned, the υ in water is lower than the velocity in the other components of ham (fat and protein+others) (Benedito et al., 2001); therefore, as the water content increases, the υ in the ham decreases. The influence of the moisture content on υ has also been reported in the curing process of *Biceps femoris* and *Longissimus dorsi* muscles and sobrassada (a dry-cured minced meat product), where the υ increased due to the dehydration (Niñoles, 2007; LLull, Simal, Benedito, & Roselló, 2002). Likewise, Koch et al. (2011a) indicated that the water loss in thawed *Longissimus dorsi* muscle entailed an increase in υ.

The water and fat contents of hams have the opposite effect on the υ and, at the same time, they show a high negative correlation in fresh hams (non-dried hams). Therefore, it is expected that, although both fat and water affect υ, there will be a relationship between the υ and each component. For a low correlation between fat and water contents, the influence of both water and fat contents on the υ should be assessed.

3.3 INFLUENCE OF FAT ON X-RAY ABSORPTIOMETRY PARAMETERS

Figure 3A shows the relationship between X-Ray attenuation values (A) obtained at different energies and the measured fat content of the hams. There was an increase in A values when the X-Ray energy decreased. This fact is linked to the greater absorption phenomena which exist at low energies than at high ones (Kalender, 2005). Whatever the energy considered, an increase in the percentage of fat content involved a decrease in A. Non-significant differences in the slope of the A *vs* X_f were detected ($p>0.05$), due to the large experimental variation of attenuation not explained by the fat content. It has been described that X-Ray attenuation at low energies is dependent on both fat content and the product thickness (Hansen et al., 2003), which is not constant in hams. The variation in ham weight could also increase the variation in A values.

A_T is proportional to the attenuation (A) and to the ratio between sample surface in the scan (S) and the ham weight (M_t) (Eq. 4). This ratio is related to the composition but also to the shape of the ham. As shown in Figure 3A, although a drop in the fat content produces an increase in A, it simultaneously increases the density and consequently, for a constant sample surface in the scan, it decreases the ratio S/M_t. Therefore, a decrease in the fat content has an opposite effect on the two factors of Eq. (4), and the resulting effect on A_T is unknown. In the present study, A_T was found to be positively correlated to the fat content at the three different voltages and intensities studied, specifically 90 kV and 4 mA ($R^2=0.57$), 70 kV and 8 mA ($R^2=0.53$) and 50 kV and 15 mA ($R^2=0.34$) (see Figure 3B).

3.4 PREDICTIVE MODELS

A linear model was established for MC set between the fat content and the ultrasonic velocity (Eq. 5); the RMSEC being 2.90% (Table 2) and $R^2=0.89$ (Eq. 5). This could be considered a robust model because very different samples were used in the study.

$$X_f\,(\%\,w.b.) = 0.54 \cdot \upsilon - 821.99 \quad \text{(Eq. 5)}$$

Where X_f is the fat content and υ is the ultrasonic velocity. The slope of Eq. (5) indicates that an increase of 1 m s^{-1} in the ultrasonic velocity led to an increase of 0.54% in the fat content.

Miles & Fursey (1977), using the reciprocal of the squared ultrasonic velocity ($1/\upsilon^2$) at 0 ºC, reported less satisfactory predictive models of fatness for comminuted beef muscles ($R^2<0.536$). These authors assessed the fat composition in meat muscles and mixtures of lean and fatty tissues. However, in the present work the fat content assessment is conducted on a much complex medium (whole bone-in ham), which includes different types of muscles, connective tissue and subcutaneous fat, which highlights the relevance of the results for implementing quality control systems in the meat industry. Miles & Fursey (1977) reported that the best temperature for conducting the ultrasonic measurements was 37ºC, however in the present work the temperature chosen was 2ºC since it is the most commonly one used for refrigeration of green hams prior to classification and processing. When analysing fresh pork *Biceps femoris* at 0 ºC, Niñoles et al. (2011) found that an increase of 1 m s^{-1} in the ultrasonic velocity implied an intramuscular fat content increase of 0.34%. The different coefficient value found by Niñoles et al. (2011) (0.34 compared to 0.54 of the present work) could be due to the great experimental variability (R^2=0.59) found by these authors, which greatly increases the standard error of the estimated coefficient. However, Park, Whittaker, Miller, and Hale (1994) suggested that the increase of 1 m s^{-1} in the ultrasonic velocity measured at 22 ºC led to a reduction of 0.21% in the fat content of *Longissimus dorsi* beef muscle, which may be explained by considering the fact that the fat melts at high temperatures.

A multiple regression analysis was performed to study the relationship between the fat and moisture contents and the ultrasonic velocity. The analyses detected a severe collinearity between both variables (the fat and moisture contents), due to the VIF being higher than 5 ($VIF_{f\text{-}w}$=8.2), caused by the inherent relationship between the fat and moisture contents in the green hams. Therefore, including the moisture content in the model does not lead to a better explanation of the experimental variability observed in the ultrasonic velocity.

The fat content was also predicted by means of X-Ray parameters (A_T) at three different energies. The predictive model (Eq. 6) showed a RMSEC of 4.20% and a R^2 of 0.80.

$$X_f\,(\%\,w.b.) = -279.643 - 0.00473 \cdot A_{T50} + 0.00806 \cdot A_{T70} - 0.00103 \cdot A_{T90} \quad \text{(Eq. 6)}$$

Predictive errors were high in comparison to what occurs using technologies in which the thickness of the sample is not critical, such as the ham grading system based on electromagnetic induction measurements (Serra, & Fulladosa, 2011), or in technologies in which thickness determination is inherent to the measurement, such as in the case of US. There are only slight X-Ray attenuation differences between fatty and lean tissues and a more accurate thickness correction (including a laser volume sensor) could help to obtain better models.

The use of hams from different animal breeds increases the robustness of the models, but may also have an adverse effect on the predictive errors. Figure 4 shows the typical geometry of scanned ham surfaces from different crossbreeds. CLW hams exhibited a different shape from CDU and CIB hams. In Eq. (4), an average thickness was used instead of the real thickness. The error of this approximation may depend on the dimensional conformation of the hams. Therefore, new models were developed by discarding the CLW hams and, thus, considering only the hams with a similar geometry. From this approach, the errors (RMSEC=2.23%) were smaller than the ones obtained using all the hams (RMSEC=4.20%), pointing to the importance of the homogeneous conformation of the hams. In contrast, since the geometry is not important in US technology, the error is similar (3.02% *vs* 2.90%) when using υ.

When using all the hams, the stepwise regression analysis including both the US and X-Ray parameters, showed that the parameter which provided the most relevant information for fat content prediction (Table 2) was the υ. The addition of X-Ray parameters to the model did not decrease the prediction error. In contrast, when discarding CLW hams, the most relevant information is provided by A_{T50} and A_{T70} and υ is not included in the model.

3.5 VALIDATION AND CLASSIFICATION TESTS

Figure 5 depicts the relationship between the fat contents measured and predicted using ultrasound (A, Eq. 5, R^2=0.90) and X-Ray (B, Eq. 6, R^2=0.67) models (Table 2). RMSEV were 2.97% and 4.65% for ultrasound and X-Rays, respectively, both providing a reliable, non-destructive measurement of the fat content of green hams over a wide range of fat content (from 6.5 to 41.0% w.b.). The number of validation errors decreases when CLW hams are excluded from the model for X-Rays (RMSEV=3.27%). Miles et al. (1987) reported standard deviations of the residuals of around 1.85 for the ultrasonic estimation of the fat content in specific sites of the beef carcass. In other studies, the ultrasonic velocity has been used to estimate the fat content of green meat mixtures and fish (Benedito et al., 2001; Ghaedian, Coupland, Decker, & McClements, 1998) obtaining a better correlation than in the present study, (R^2=0.99, in both cases). In all likelihood, this fact could be explained by considering that highly homogeneous samples were tested in the former studies. The green hams used in the present study, however, are heterogeneous; this is due to several factors, the fat distribution within the samples, the connective tissue characteristics, the different moisture and fat profiles and the existing bones and skin, among others.

In order to evaluate the feasibility of using the ultrasonic and X-Ray models to classify the hams into different categories according to their fat content, the MV set hams (Table 1) were classified into three groups: low (<14%), medium (between 14 and 26%) and high (>26%) fat content levels (Table 3). Once the estimated fat content was calculated from Eq. (5) and (6) and compared with the measured one, the classification performance was assessed. In average terms, whereas the ultrasonic model classified 88.5% correctly, the X-Ray model only classified 65.4% of the MV ham set (Table 3). The ultrasonic model was able to correctly classify 87.5 and 100.0% of the ham pieces, in the low and high fat content groups, respectively. However, for a medium fat content, the percentage of correctly classified hams was reduced to 75.0% (Table 3). In contrast, the X-Ray model provided similar percentages for every category.

Thus, US could better classify hams into different groups of fatness, which would be highly relevant for industrial quality control purposes. It would be necessary to develop a prototype which permits a rapid measurement before implementing this technology industrially as a means of easily and rapidly sorting and processing the raw material according to the fat content. X-Rays could also be useful, especially if a specific calibration is developed for each kind of raw material in order to overcome the variability produced by the different conformation of the hams. In this case, the device is already suitable for industrial conditions and works at production speed.

As previously explained, it is not worth combining X-Ray and US sensors together in an instrument because it does not offer a significant improvement and it would increase the cost of the device.

4. CONCLUSIONS

Ultrasound velocity and X-Ray attenuation are influenced by the composition of the hams, allowing predictive models to be developed for the fat content with errors of 2.97% and 4.65% for US and X-Ray, respectively, when all the hams are used. When discarding hams with a different geometry (CLW hams), the X-Ray predictive error improved, decreasing to 3.27%. Nevertheless, in no case did the combination of parameters obtained from both technologies improve the prediction accuracy. These predictive models permitted a satisfactory classification of the hams into three fat levels (<14, 14-26 and >26% fat content), demonstrating the feasibility of these non-destructive techniques for ham classification purposes. Research should be conducted in order to include accurate sample geometry corrections in the X-Ray technique and to develop fast ultrasonic devices to be used online.

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REFERENCES

Association of Official Analytical Chemists (2007). Official method 2007.04, Determination of Fat, Moisture, and Protein in Meat and Meat Products. Official Methods of Analysis of AOAC International (18th ed.), Association of Official Analytical Chemists International, Gaithersburg, MD.

Benedito, J., Carcel, J. A., Rosello, C., & Mulet, A. (2001). Composition assessment of raw meat mixture using ultrasonics. *Meat Science*, 57, 365-370.

Blasco, A., Gou, P., Gispert, M., Estany, J., Soler, J., Diestre, A., & Tibau, J. (1994). Comparison of five types of pig crosses. I. Growth and carcass traits. *Livestock Production Science*, 40(2), 171-178.

Brienne, J. P., Denoyelle, C., Baussart, H., & Daudin, J. D. (2001). Assessment of meat fat content using dual energy X-Ray absorption. *Meat Science*, 57(3), 235-244.

Čandek-Potokar, M., & Škrlep, M. (2012). Factors in pig production that impact the quality of dry-cured ham: A review. *Animal*, 6(2), 327-338.

Chanamai, R., & Mc.Clements, D. J. (1999). Ultrasonic determination of chicken composition. *Journal Agricultural Food Chemistry,* 47, 4686-4692.

Cierach, M., & Modzelewska-Kapitula, M. (2011). Effects of ph values and fat content on sodium chloride diffusion rate in pork. *Journal of Food Processing and Preservation,* 35, 129-142.

Corona, E., García-Pérez, J. V., Ventanas, S., & Benedito, J. (2014). Ultrasonic characterization of the fat source and composition of formulated dry-cured meat products. *Food Science and Technology International*, 20(4), 275-285.

Font-i-Furnols, M., Brun, A., Tous, N., & Gispert, M. (2013). Use of linear regression and partial least square regression to predict intramuscular fat of pig loin computed tomography images. *Chemometrics and Intelligent Laboratory Systems*, 122, 58-64.

Fulladosa, E., Muñoz, I., Serra, X., Arnau, J., & Gou, P. (2014). X-Ray absorptiometry for non-destructive monitoring of the salt uptake in bone-in raw hams during salting. *Food Control*. DOI: 10.1016/j.foodcont.2014.06.023.

Garcia-Gil, N., Santos-Garcés, E., Muñoz, I., Fulladosa, E., Arnau, J., & Gou, P. (2012). Salting, drying and sensory quality of dry-cured hams subjected to different pre-salting treatments: Skin trimming and pressing. *Meat Science*, 90(2), 386-392.

Ghaedian, R., Coupland, J. N., Decker, E. A., & McClements, D. J. (1998). Ultrasonics determination of fish composition. *Journal of Food Engineering,* 35, 323-337.

Hansen, P. W., Tholl, I., Christensen, C., Jehg, H. C., Borg, J., Nielsen, O., Østergaard, B., Nygaard, J., & Andersen, O. (2003). Batch accuracy of on-line fat determination. *Meat Science*, 64, 141-147.

ISO 1442 (1997). Meat and meat products. Determination of moisture content (Reference method). International organization for standardization, Geneva.

Kalender, W. A. (2005). *Computed tomography: Fundamentals, system technology, image quality, applications.* (2nd ed.) Erlangen, Germany: Publicis. Corperate Publishing (p. 304).

Kinsler, L. E., Frey, A. R., Coppens, A. B., & Sanders, J. V. (1982). *Fundamentals of Acoustics.* (3 rd ed.) New York, U.S.A.: John Wiley and Sons (Chapter 4).

Koch, T., Brand, S., Lakshmanan, S., Raum, K., Wicke, M., & Mörlein, D. (2011a). Ultrasound velocity and attenuation of porcine soft tissues with respect to structure and composition: I. Muscle. *Meat Science*, 88, 51-58.

Koch, T., Lakshmanan, S., Brand, S., Wicke, M., Raum, K., & Mörlein, D. (2011b). Ultrasound velocity and attenuation of porcine soft tissues with respect to structure and composition: II. Skin and backfat. *Meat Science*, 88, 67-74.

LLull, P., Simal, S., Benedito, J. & Roselló, C. (2002). The use of ultrasound velocity measurement to evaluate the textural properties of sobrassada from Mallorca. *Journal of Food Engineering*, 52, 323-330.

López-Campos, O., Larsen, I., Prieto, N., Juárez, M., & Aalhus, L. (2013). Preliminary evaluation of dual energy x-Ray absorptiometry to assess intramuscular fat from the *Longissimus Thoracis* muscle of beef. *E-Book of proceedings of the 59th International Congress of Meat Science and Technology.* (S7B-17), Izmir, Turkey.

McClements, D. J., & Povey, M. J. W. (1992). Ultrasonic analysis of edible fats and oils. *Ultrasonics*, 30, 383-388.

Mercier, J., Pomar, C., Marcoux, M., Goulet, F., Thériault, M., & Castonguay, F. W. (2006). The use of dual-energy X-Ray absorptiometry to estimate the dissected composition of lamb carcasses. *Meat Science*, 73(2), 249-257.

Miles, C.A., & Fursey, G.A.J. (1977). Measurement of the fat content of meat using ultrasonic waves. *Food Chemistry*, 2(2), 107-118.

Miles, C.A., Fisher, A.V., Fursey, G.A.J., & Page, S.J. (1987). Estimating beef carcass composition using the speed of ultrasound. *Meat Science*, 21(3), 175-188.

Miles, C.A., Fursey, G.A.J., Page, S.J., & Fisher, A.V. (1990). Progress towards using the speed of ultrasound for beef leanness classification. *Meat Science*, 28(2), 119-130.

Niñoles, L. (2007) *Contribución a la caracterización de la calidad de productos de cerdo mediante ultrasonidos de señal.* (PhD thesis) Spain: Universitat Politècnica de València.

Niñoles, L., Mulet, A., Ventanas, S., & Benedito, J. (2011). Ultrasonic characterization of *B. femoris* from iberian pigs of different genetics and feeding systems. *Meat Science*, 89, 174-180.

Niñoles, L., Sanjuan, N., Ventanas, S., & Benedito, J. (2008). Ultrasonic and sensory characterization of dry-cured ham fat from iberian pigs with different genetics and feeding backgrounds. *Meat Science*, 80(3), 896-902.

Park, B., Whittaker, A. D., Miller, R. K., & Hale, D. S. (1994). Predicting fat in beef Longissumus muscle from speed of sound. *Journal of Animal Science*, 72, 109-116.

Picouet, P. A., Muñoz, I., Fulladosa, E., Daumas, G., & Gou, P. (2014). Partial scanning using computed tomography for fat weight prediction in green hams: Scanning protocols and modelling. *Journal of Food Engineering* DOI: 10.1016/j.jfoodeng.2014.06.012

Serra, X., & Fulladosa, E. Online total fat prediction in green hams. (2011). Newsletter Q-PorkChains, 8, 8. Retrieved from http://www.q-porkchains.org/news/~/media/Qpork/docs/pdf/newsletter/QPorkChains_Newsletter_8_march2011.ashx

Vester-Christensen, M., Erbou, S. G. H., Hansen, M. F., Olsen, E. V., Christensen, L. B., Hviid, M., Ersbøll, B. K., & Larsen, R. (2009). Virtual dissection of pig carcasses. *Meat Science*, 81(4), 699-704.

Figure 1. The experimental set-up used in the ultrasonic **(A)** and X-Ray **(B)** measurements and the location of ultrasonic measurement zones. C. Cushion, FC. Fore cushion and BE. Butt end.

Figure 2. Relationship between the ultrasonic velocity and the fat (X_f) **(A)** and moisture contents (X_w) **(B)** of raw hams.

Figure 3. Relationship between X-Ray parameters, A **(A)** and A_T **(B)**, obtained at different X-Ray energies (50, 70 and 90 kV) and the fat content (X_f) of raw hams.

Figure 4. Scanned surface of hams from crosses containing Large white and Landrace (A), Duroc (B) or Iberian (C) breeds.

Figure 5. Validation of the predictive model for the estimation of the fat content (X_f) of raw hams based on ultrasonic (A) and X-Ray absorptiometry (B) measurements.

Figure 1

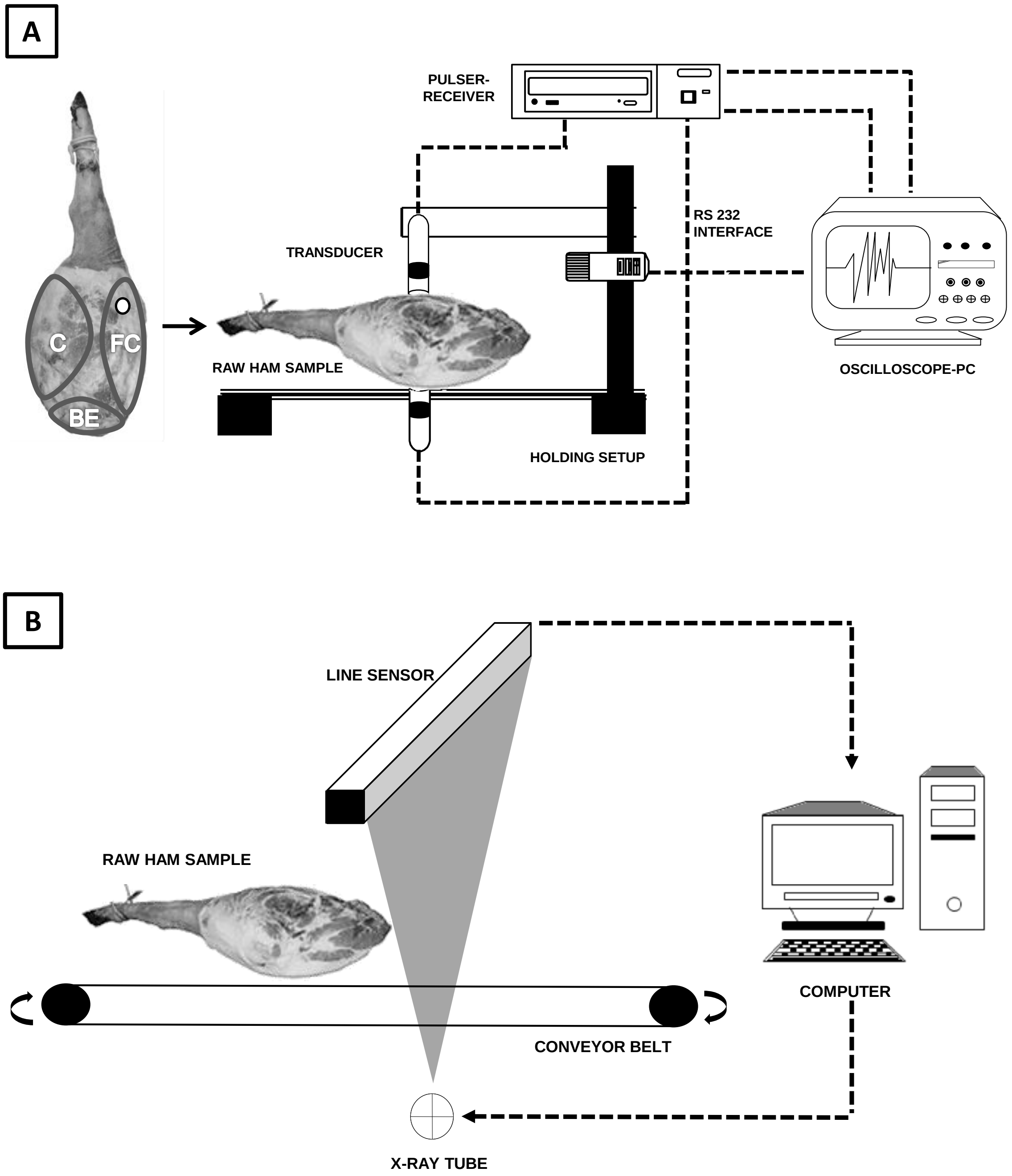
A
C
FC
BE
PULSER-
RECEIVER
TRANSDUCER
RS 232
INTERFACE
RAW HAM SAMPLE
HOLDING SETUP
OSCILLOSCOPE-PC
B
LINE SENSOR
RAW HAM SAMPLE
COMPUTER
CONVEYOR BELT
X-RAY TUBE

Figure 2

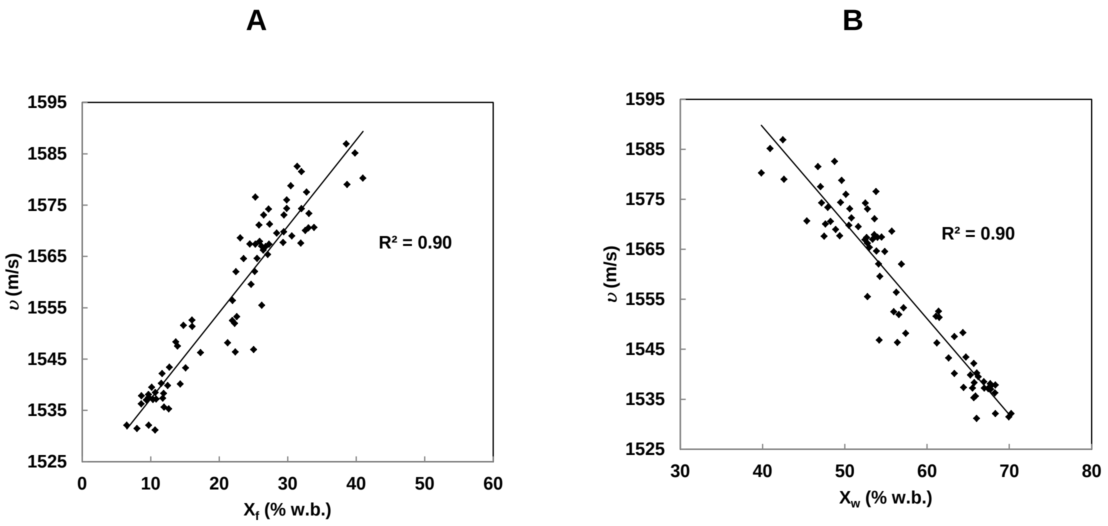
A
B
1595
1585
1575
1565
1555
1545
1535
1525
υ (m/s)
R² = 0.90
0
10
20
30
40
50
60
X_f (% w.b.)
30
40
50
60
70
80
X_w (% w.b.)

Figure 3

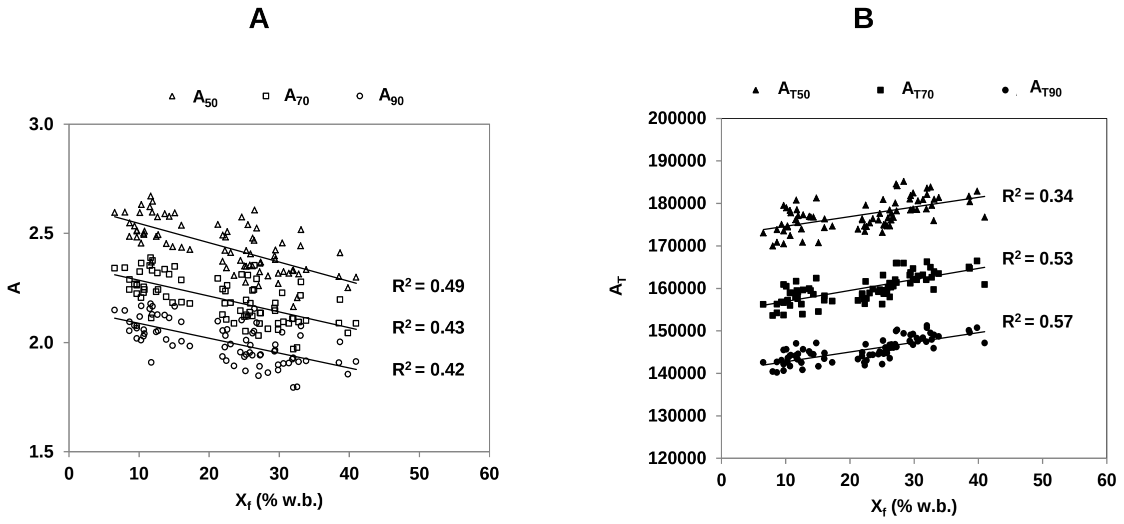
A
A_{50} A_{70} A_{90}
3.0
2.5
2.0
1.5
A
0 10 20 30 40 50 60
X_f (% w.b.)
$R^2 = 0.49$
$R^2 = 0.43$
$R^2 = 0.42$
B
A_{T50} A_{T70} A_{T90}
200000
190000
180000
170000
160000
150000
140000
130000
120000
A_T
0 10 20 30 40 50 60
X_f (% w.b.)
$R^2 = 0.34$
$R^2 = 0.53$
$R^2 = 0.57$

Figure 4

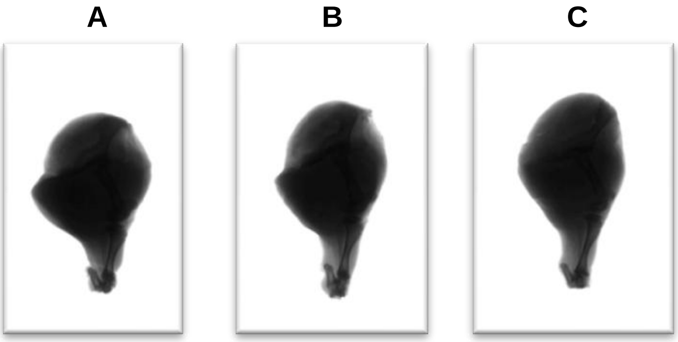

Figure 5

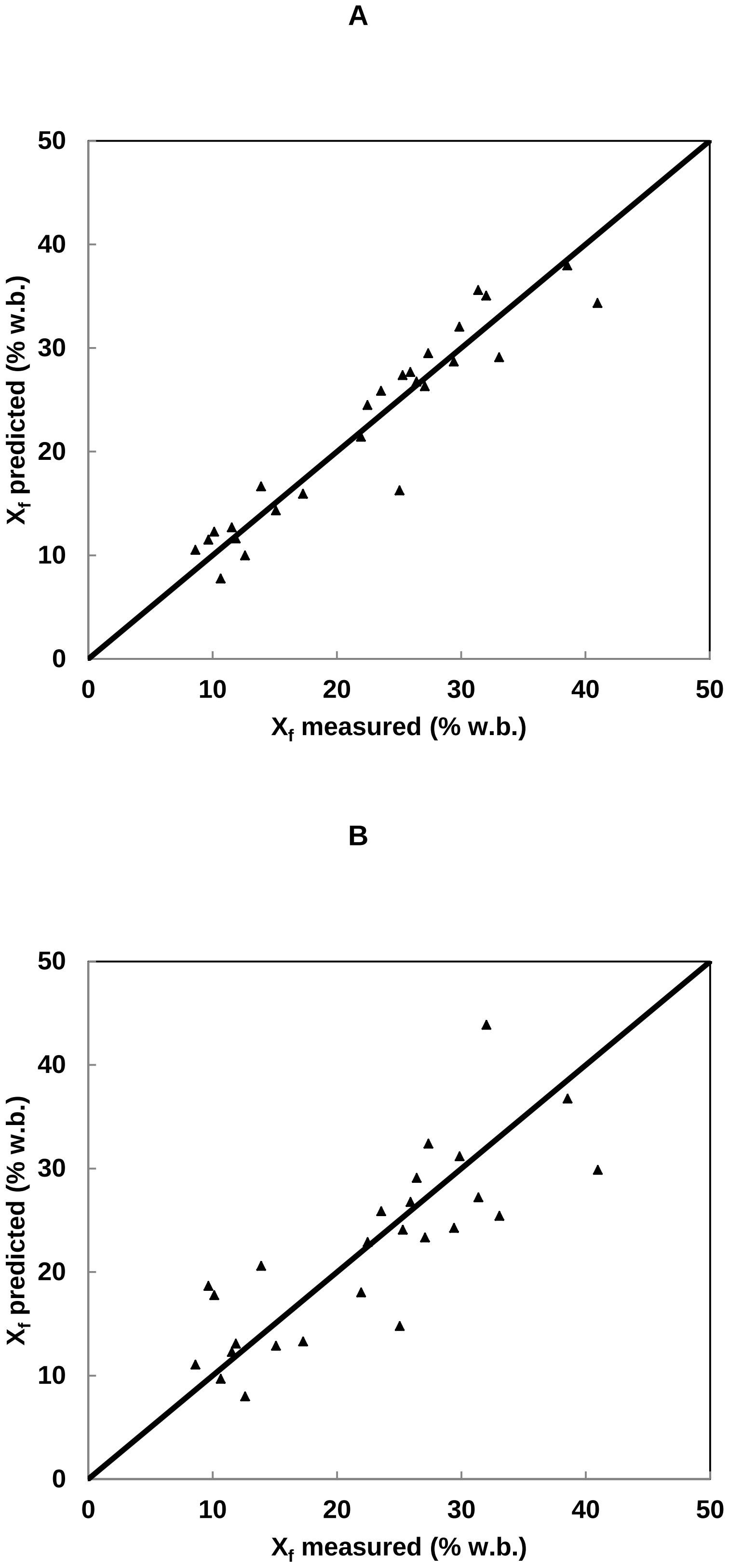
A
0
10
20
30
40
50
X_f predicted (% w.b.)
0
10
20
30
40
50
X_f measured (% w.b.)
B
0
10
20
30
40
50
X_f predicted (% w.b.)
0
10
20
30
40
50
X_f measured (% w.b.)

Table 1

Table 1. Average, minimum and maximum values of moisture (X_w % w.b.) and fat (X_f % w.b.) contents for validation and calibration ham sets.

	n	**X_w (% w.b.)**			**X_f (% w.b.)**		
		MEAN	**MIN**	**MAX**	**MEAN**	**MIN**	**MAX**
CALIBRATION (MC)	52	57.0	40.9	70.2	21.7	6.5	39.8
VALIDATION (MV)	26	56.4	39.9	68.3	22.4	8.6	41.0

Table 2

Table 2. Parameters of predictive models for fat content of raw hams using X-Ray and ultrasound measurements.

Crossbreeds used	Technology	MODEL VARIABLES	RMSEC(%)	R^2	RMSEV(%)
CLW, CDU, CIB	**US**	υ	2.90	0.89	2.97
CLW, CDU, CIB	**X-Rays**	A_{T50} ,A_{T70}, A_{T90}	4.20	0.80	4.65
CDU, CIB	**US**	υ	3.02	0.59	3.29
CDU, CIB	**X-Rays**	A_{T50} ,A_{T70}, A_{T90}	2.23	0.79	3.27

Table 3

Table 3. Classification of raw hams according to the fat content (X_f) (low X_f<14%, medium 14≤X_f≤26% and high X_f>26%) by using the predictive model based on ultrasonic and X-Ray measurements.

FAT LEVEL	X_f (% w.b.)	% CLASSIFICATION	
		US	X-Rays
LOW	<14	87.5	70.0
MEDIUM	14-26	75.0	62.5
HIGH	>26	100.0	75.0
TOTAL		88.5	65.4