APPLICATIONS OF X-RAY MULTI ENERGY SPECTROMETRY FOR THE MEAT INDUSTRY

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Abstract – Changes on composition, on density or structure of tissues produce variations on the X-ray multi energy spectra. This work addresses the use of X-ray multi energy spectrometry to predict and characterize different parameters of meat products. Feasibility of this technology to monitor beef tenderization process, to compare bones density and to determine salt content and texture defects in dry-cured ham was evaluated. It showed a good capacity to follow the beef tenderization process and to compare densities from bones with similar height. Changes caused by induced proteolysis in dry-cured ham were also quantified. Salt content was determined with an error of 0.410%. It can be concluded that this technology could be useful for various applications in the meat industry.

Key Words – characterization, control, non-destructive.

I. INTRODUCTION

X-ray technologies are based on the differential X-ray attenuation produced by the scanned product depending on its characteristics. The advantage of X-ray in comparison to other technologies is the capability to fully penetrate the product and to analyse non-destructively the inner part of the samples. The degree of attenuation is influenced by the product density, the atomic number, the thickness of the samples and the incident X-ray energy [1].

These technologies have been reported to be useful for different applications in the food industry. Computed tomography allows to determine lean meat percentage of carcasses and to monitor on line salt and water contents during curing process. DEXA allows determining the texture of beef, fat content of meat products and bones density. Simple inspectors were also useful to determine fat and salt contents in raw and processed hams on line.

Gorecki *et al.* [2] reported that a recently developed multi energy detector was able to acquire not only the global X-ray attenuation per pixel but also the energy of X-rays arriving to the detector. For this reason, a more accurate evaluation of some meat products characteristics using these sensors is expected.

The aim of the present work is to show the feasibility of different potential applications of X-ray multi energy spectrometry for meat industry. Feasibility to monitor beef tenderization process, to determine differences in bones density and to characterize salt content and texture of cured products was evaluated.

II. MATERIALS AND METHODS

a. *Description of the X-ray multi energy device*

An X-ray multi energy device (MXVPACK4010, Multiscan Technologies, Cocentaina, Spain) was used to scan the samples. It has an X-ray spectrometric detector with a pixel size of 0.8 mm. A convertor belt moves the samples along at a speed of 10 m/min while the X-rays are being emitted from below the samples. The system acquires an image (1000x256 pixels) of the samples in which each pixel contains an X-ray energy spectrum of 128 channels (from 20 to 160 keV).

b. Data treatment

In order to analyse the feasibility of different applications, specific regions of interest (ROI) from each sample, were selected on each image. In some cases, the attenuation raw data for each energy channel was used. In other cases, these selected ROIs were analysed using a Matlab script written in house (MATLAB, Ver. 7.7.0, The Mathworks Inc., Natick, MA, USA). The mean X-ray attenuation (S_a) for the energy channel *a* of the selected ROI was calculated after background correction and log transformation as described in equation 1.

$$S_a = \frac{-\sum_{i=1}^{p} \ln\left(\frac{I_f^{a,i}}{I_o^{a,i}}\right)}{p} \qquad \text{(Eq 1)}$$

where I_f is the intensity of the transmitted radiation and I_o is the energy of the incident radiation at each pixel i of the ROI which contains p pixels. The calculation is done for each energy channel a, that ranges from 1 to 128. According to Eq 1, an increase of S_a value represents an increase of the X-ray attenuation.

The mean attenuation value of different energy bands (EB) of the energy spectra was also calculated. Energy band is defined as the average over several energy channels of the mean attenuation S_a and was calculated as follows (Eq 2):

$$EB_{x-y} = \frac{\sum_{a=x}^{y} S_a}{y-x+1} \qquad \text{(Eq. 2)}$$

x and y correspond to the first and last energy channel a of the energy band considered. Energy bands investigated contained 20 channels.

c. *Experimental procedure*

Monitoring of beef tenderization: Three beef samples (9 cm diameter and 5 cm height) were vacuum-packed using a plastic mold to keep its shape and height. Samples were scanned at 110 kV and 1.5 mA during tenderization process (0, 5, 20, 30 and 40 days). Meanwhile, samples were kept at 25ºC. An ANOVA test was used to determine significant differences during the process ($p<0.05$). Linear model included sample and tenderization time as fixed effect.

Bones density determination: Ten tibias and femurs from pigs fed with different diets (n=5 pigs/diet), one diet with the recommended phosphorus levels (normP) and another with restriction of phosphorus (lackP), were scanned separately at 150 kV and 3 mA. The raw attenuation values obtained were used to obtain an image by means of a Matlab script written in house. The density of these bones was previously determined from computed tomography images using the equation reported by Picouet *et al.* [3]. ANOVA test was performed to determine differences between diets and between bones using the average attenuation value of the 128 energy channels. Diet and bones were included as fixed effects in the model.

Dry-cured ham proteolysis evaluation: Twenty-two commercial dry-cured ham packages 2.5 cm thick, with 12 slices inside were used. Proteolysis was induced by spreading 0.125 mL of a proteolytic enzyme (Delvolase®, DSM Food Specialties, France) on all the faces of each slice of the package and vacuum packaged again. They were scanned at 110 kV and 1.5 mA after several exposure times to the proteolytic enzyme (0h, 2h, 4h, 6h, 8h, 24h and 48h). Meanwhile, samples were kept at 25ºC. According to Rubio *et al.* [4] different exposure times can be related to different defective texture level. An ANONA test was used to determine significant differences ($p<0.05$). Sample and exposure time were included as fixed effect in the model.

Salt content determination in dry-cured ham: One hundred sixty, 2 cm-thick slices of dry-cured ham containing different salt and water contents were scanned at 110 kV and 1.5 mA. A partial least square regression (PLSR) analysis with 15 factors was used to develop and validate the predictive models to estimate the salt content.

III. RESULTS AND DISCUSSION

Monitoring of beef tenderization

Significant differences between the acquired spectra during tenderization process were found ($p<0.05$). There is a decrease of X-ray attenuation of the spectra that is also observed when analysing the mean attenuation for the energy bands (Table 1). These differences are more or less pronounced depending on the energy bands, showing a different discrimination power of tenderization levels for the different regions of the spectra.

Table 1. Mean of X-ray attenuation for different energy bands of the spectra during tenderization.

Days	**EB$_{1-20}$**	**EB$_{21-40}$**	**EB$_{41-60}$**	**EB$_{61-80}$**	**EB$_{81-100}$**
0	1.26^{a}	0.89^{a}	0.95^{a}	1.27^{a}	2.08^{a}
5	1.25^{ab}	0.87^{a}	0.93^{a}	1.28^{a}	2.08^{a}
20	1.22^{bc}	0.84^{b}	0.91^{b}	1.26^{a}	2.04^{b}
30	1.21^{c}	0.85^{b}	0.89^{c}	1.19^{b}	1.97^{c}
40	1.19^{c}	0.84^{b}	0.88^{c}	1.19^{b}	1.91^{c}

^{abc} Within columns, different letters indicate significant differences ($p<0.05$).

Bones density determination

Figure 1 shows the images of the tibia and the femur bones from the two feeding treatments. Within bones, those who came from lackP animals presented lower attenuation, indicating they are less dense than those from normP animals. Analysis of variance confirmed differences in the average attenuation value between diets and between bones ($P<0.01$). These results are in agreement with the density calculated by means of CT: 1.33 and 1.86 g/cm^3 for tibia from lackP and normP animals, respectively; and 1.40 and 1.75 g/cm^3 for femur from lackP and normP animals, respectively. Nevertheless, it is important to remark that the average attenuation from raw data can only be used to compare densities within bones since they have similar size. Attenuation is highly related with the height of the scanned object and, without transforming this factor, the results could be confusing. Thus, if objects of different size need to be compared, a correction for the height (thickness) must be previously applied.

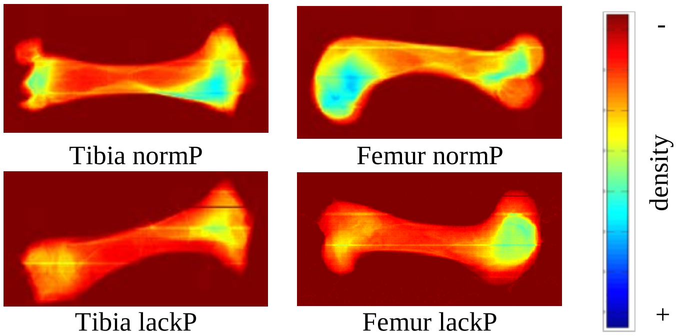

Figure 1. Images of tibia and femur from a normP and a lackP animal. Colour scale is related with the density (the higher the value, the lower the density).

Dry-cured ham proteolysis evaluation

Figure 2 shows the mean attenuation spectra after different proteolysis induction times from *Biceps femoris* muscle. Statistical analyses show a significant decrease of the attenuation when increasing time of exposure to enzyme (closely related to proteolysis and pastiness intensity) along all the spectra. This variation is attributed to the degradation of the tissues when increasing time of exposure to the enzyme.

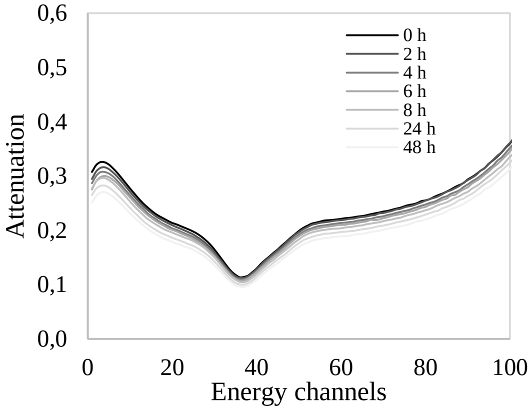

Figure 2. Mean energy spectra obtained from *Biceps femoris* muscle of dry-cured ham at different proteolysis induction times (0, 2, 4, 6, 8, 24 and 48 hours).

Salt content determination in dry-cured ham

Figure 3 shows the relation between the predicted and measured salt content (%) of *Biceps femoris* dry-cured ham slices. A RMSEV of 0.410% and R^2 of 0.837 were obtained. These errors are similar to those obtained using other devices to predict salt content [5, 6].

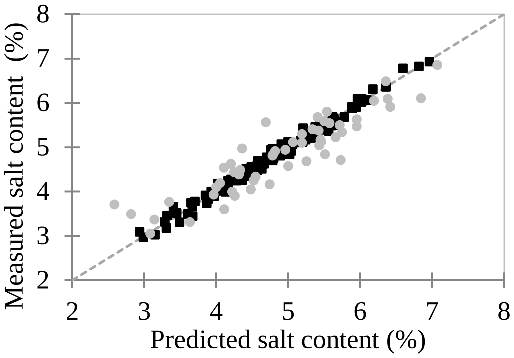

Figure 3. Relationship between measured and predicted NaCl. Calibration (■) and validation (●) samples. The discontinuous line represents the perfect 1:1 relationship between x and y.

IV. CONCLUSION

It can be concluded that X-ray multi energy technology permits following tenderization process in raw beef and identifying differences in bones density if thickness is similar. It can also determine differences of proteolysis and salt content in dry-cured ham. X-ray multi energy spectrometry is a technology that has potential for several applications in the industry. However, feasibility of these determinations at industrial level needs to be evaluated.

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