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Including estimated intramuscular fat content from computed tomography images improves prediction accuracy of dry-cured ham composition

Eva Santos-Garcés, Israel Muñoz, Pere Gou, Núria Garcia-Gil, Elena Fulladosa *

IRTA, XaRTA, Food Technology, Finca Camps i Armet, E-17121 Monells, Spain

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ABSTRACT

In recent years, computed tomography (CT) has been proposed as a method for the non-destructive prediction of salt content, water content and water activity (a_w) in dry-cured ham. However, fat produces an important disturbance in the predictions. The aim of this study was to determine the effect of including an intramuscular fat content (IMF) estimate in the predictive models on the model predictability and CT tube voltage requirements. CT tomograms were obtained at three voltages. IMF was estimated by image analysis of CT tomograms obtained at the lowest voltage. By including an IMF estimate in the model, the prediction error was reduced by more than half in the water and a_w predictions, but had little effect on the salt prediction. Additionally, the amount of CT voltages required in the predictive model decreased from three to two for salt and a_w predictions.

1. Introduction

In recent years, computed tomography (CT) has been successfully introduced into the meat industry as a non-destructive tool for a wide range of applications such as carcass classification (Font i Furnols, Teran, & Gispert, 2009; Picouet, Teran, Gispert, & Font i Furnols, 2010; Vester-Christensen et al., 2009). The use of CT to correctly distinguish salt in cured meat products was also described by Sørheim and Berg (1987a,b) and Frøystein, Sørheim, Berg, and Dalen (1989). Mathematical models were later proposed to determine salt content (Fulladosa, Santos-Garcés, Picouet, & Gou, 2010; Håseth et al., 2008; Santos-Garcés, Gou, Garcia-Gil, Arnau & Fulladosa, 2010a; Vestergaard, Risum, & Adler-Nissen, 2004), water content (Fulladosa et al., 2010; Santos-Garcés et al., 2010a; Santos-Garcés et al., 2010b) and water activity (a_w) (Santos-Garcés et al., 2010a; Santos-Garcés et al., 2010b) under different conditions and at different stages of the dry-cured ham elaboration process. CT analytical tools, in combination with the prediction models mentioned above, have been developed to provide quantitative information on local salt content, water content and a_w, and their distribution within the ham throughout the process (Santos-Garcés, Muñoz, Gou, Sala, & Fulladosa, 2012).

These CT analytical tools have also been used to monitor and compare different salting processes (Santos-Garcés et al., 2012), to evaluate hams subjected to different pre-salting treatments, such as skin trimming or pressing (Garcia-Gil et al., 2012), and to estimate NaCl diffusivity in the *Semimembranosus* (SM) muscle during the salting process (Picouet, Gou, Fulladosa, Santos-Garcés, & Arnau, 2012).

The main drawback of the abovementioned CT based models is the disturbance that fat produces in the predictions (Vestergaard, Erbou, Thauland, Adler-Nissen, & Berg, 2005; Håseth, Egelandsdal, Bjerke, & Sørheim, 2007; Håseth et al., 2008; Fulladosa et al., 2010; Santos-Garcés et al., 2010a; Santos-Garcés et al., 2010b; Santos-Garcés et al., 2012). Intramuscular fat content (IMF) produces an increase of the prediction errors, mainly in the water content and a_w predictions. Several studies have reported that prediction errors significantly decreased when fatty samples were discarded (Fulladosa et al., 2010; Håseth et al., 2007) or when fat content was included in the models (Håseth et al., 2007; Santos-Garcés et al., 2010a; Santos-Garcés et al., 2010b). Nevertheless, although Font-i-Furnols, Brun, Tous, and Gispert (2013) described CT as a promising tool for the determination of IMF in raw pork meat by means of image analysis, estimation of IMF in samples subjected to a salting process is not straightforward, because salted-fat presents higher attenuation values than non-salted fat (due to the higher density of Na^+ and Cl^- ions) and it might be recognized as false lean. In dry-cured ham, only the subcutaneous fat and the intermuscular fat have been successfully segmented from CT tomograms using image analysis (Santos-Garcés et al., 2012).

The aims of this study were (1) the non-destructive estimation of IMF in dry-cured ham muscles by image analysis of CT tomograms, and (2) the improvement of CT based models for predicting salt content, water content, and a_w through the inclusion of an IMF estimate in the models.

* Corresponding author. Tel.: +34 972630052; fax: +34 972630980.
E-mail address: elena.fulladosa@irta.cat (E. Fulladosa).

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2. Material and methods

2.1. Hams

Sixty-three commercial hams were obtained from seven different producers at different stages of the dry-curing process: resting ($n = 15$), drying ($n = 15$), and end of process ($n = 33$). The hams came from different crossbreeds (Landrace × Large white sows crossed with Duroc, Large white or Landrace sires) representing the industrial market in terms of salt, water and fat contents. The total process length depended on each producer, covering a range from 5 to 24 months of curing.

2.2. Computed tomography scanning

The CT scanning of the hams was performed using a scanner model HiSpeed Zx/i from General Electric Healthcare (GE Healthcare, Barcelona, Spain). An axial protocol was used with settings of 80, 120 and 140 kV, 250 mA and rotation time of 2 s. Image size was 512 × 512 pixels and Displayed Field of View (DFOV) was 461 × 461 mm^2. The algorithm STD+ from General Electric was used to reconstruct the images (Fulladosa et al., 2010) as it gave a high contrast spatial resolution in samples containing soft tissue (lean and fat) and mineral phases (mainly NaCl). Each pixel had a squared area of 0.81 mm^2 and had three CT values expressed in Hounsfield Units (HU) obtained at 80, 120, and 140 kV tube voltages (HU_{80}, HU_{120} and HU_{140}, respectively). Matrices of HU values were saved and retrieved with Matlab software (MATLAB, Ver. 7.7.0, The Mathworks Inc., Natick, MA, USA) for further automatic analysis.

Two consecutive 10 mm thick tomograms were obtained from each ham at 10 cm from the aitch bone in the distal direction (the widest part of the ham) in order to have enough sample for chemical analysis (Fig. 1A). From each tomogram, three different Regions of Interest (ROIs) were selected from different zones of the slice to achieve a wide range of compositions, in terms of salt, water, and fat content. ROI 1 contained the *Biceps femoris* (BF) muscle, ROI 2 contained the *Semitendinosus* (ST) muscle, and ROI 3 contained the *Semimembranosus* (SM) muscle (Fig. 1B). The average CT value of the two consecutive tomograms was calculated, obtaining for each ROI, values of HU_{80}, HU_{120} and HU_{140}.

2.3. IMF estimate by image analysis of CT tomograms

Matlab scripts written in-house were developed to analyze specific ROIs of the matrices of values obtained from the tomograms. For each ROI, IMF was segmented using edge detection based on the discrete Fourier transform (Rangayyan, 2004). IMF could not be segmented using a simple threshold operation because HU values of IMF depend on the salt content of the ham. Therefore, a global threshold value could not be applied to the segmentation of IMF across hams with different salt contents. Since IMF appears in CT images as streaks of lower HU values than their surrounding voxels, gradient based techniques were more suitable than simple threshold operations. Several techniques were tested before using Fourier Transform. The best results were obtained by segmenting IMF by applying the discrete Fourier transform (DFT) to the image and a Gaussian high pass filter with a cut-off frequency of 50. After filtering, the images were transformed back using the inverse discrete Fourier transform and pixels with HU_{80} values equal to or below −5 were labeled as IMF by a threshold operation (Fig. 1C). The area of the matrix (number of pixels) considered as IMF was expressed as percentage of IMF area (IMF area (%)) which was calculated as the ratio IMF area/total area.

For the segmentation of IMF all the three energies (80, 120 and 140 kV) were equally useful. However, the combination of two or more energies did not improve the accuracy of the segmentation of IMF. Matrices of HU_{80} values were finally used because 80 kV is the energy which provides the maximum information when models incorporated only one energy for the prediction of salt and water content (Fulladosa et al., 2010).

The image analysis was not accurate enough to properly distinguish IMF present in SM muscle when the salt gradient was high (after salting). Therefore, ROI 3 (from SM muscle) from hams during the early resting was discarded.

2.4. Sample preparation and chemical analysis

The sampling of ROIs 1 and 2 was performed as described by Fulladosa et al. (2010). The ROIs were cut out of the ham slices and immediately vacuum packed in plastic bags. Each sample was minced, homogenized and analyzed for salt, water and fat contents, and a_w.

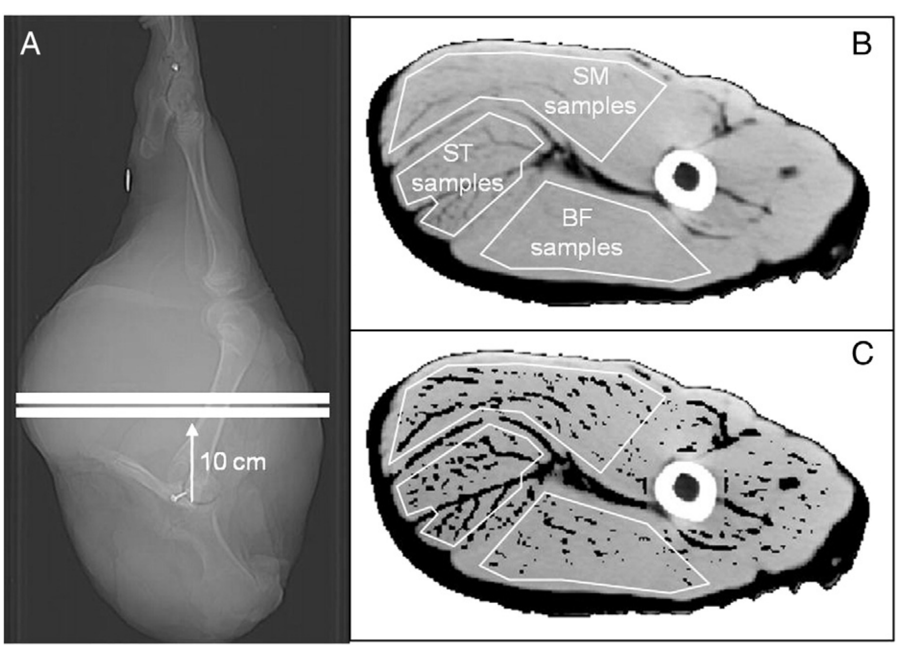

Fig. 1. CT scan location (A). Cross-sectional CT image (tomogram) obtained at 80 kV, in which sampled ROIs from *Semimembranosus* (SM), *Biceps femoris* (BF) and *Semitendinosus* (ST) muscles are indicated (B). CT image after segmentation, where intramuscular fat is illustrated by the black area within each ROI (C).