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Tools for Studying Dry-Cured Ham Processing by Using Computed Tomography

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ABSTRACT: An accurate knowledge and optimization of dry-cured ham elaboration processes could help to reduce operating costs and maximize product quality. The development of nondestructive tools to characterize chemical parameters such as salt and water contents and a_w during processing is of special interest. In this paper, predictive models for salt content (R^2 = 0.960 and RMSECV = 0.393), water content (R^2 = 0.912 and RMSECV = 1.751), and a_w (R^2 = 0.906 and RMSECV = 0.008), which comprise the whole elaboration process, were developed. These predictive models were used to develop analytical tools such as distribution diagrams, line profiles, and regions of interest (ROIs) from the acquired computed tomography (CT) scans. These CT analytical tools provided quantitative information on salt, water, and a_w in terms of content but also distribution throughout the process. The information obtained was applied to two industrial case studies. The main drawback of the predictive models and CT analytical tools is the disturbance that fat produces in water content and a_w predictions.

KEYWORDS: *Computed tomography, dry-cured ham, predictive models, salt, water, a_w, CT analytical tools*

INTRODUCTION

The elaboration of dry-cured ham follows traditional systems that have been used for years, in which salting is an essential part of the operation. These systems can provide products with a wide variation, even within the same batch, in terms of salt and water contents. The main variations of these parameters are due not only to the raw material characteristics (pH, overall fat content, impedance)[1−4] but also to the processing and conditions to which the raw hams have been submitted.[5−7]

Salt is an important ingredient for the reduction of a_w. Because a_w usually correlates well with potential microbial growth, this information may be extremely useful for predicting the microbial stability and safety of foods.[8,9] For this reason, the nondestructive determination of a_w is of special interest in the most critical parts of the ham (e.g., the *Biceps femoris* muscle), where these microbiological hazards usually occur, especially in reduced-salt products.

Governments and health agencies encourage the food industry to reduce the salt content of their products to prevent health problems, but reduction of this preservative agent is not straightforward, and nondestructive methods such as computed tomography (CT) may be helpful. CT is an X-ray-based method that permits the prediction of the salt[10,11] and water contents[12,13] and a_w [13,14] in dry-cured ham throughout the elaboration process. Acquired information can help to develop new manufacturing processes or to improve the existing ones. Nevertheless, suitable analytical tools to evaluate the overall salt and water contents and a_w distribution in a slice or to objectively compare different regions during the elaboration process are needed.

The usefulness of CT methods and related tools to study dry-cured ham processes has been reported in previous studies. Sørheim and Berg[15,16] reported that CT offered a picture of salt distribution in dry-cured ham after resting and highlighted differences of salt uptake depending on the quality of the hams (fresh or frozen/thawed). More recently, Vestergaard et al.[17] used line profiles to estimate salt gradients in a meat model system (loin pork). In addition, Vestergaard et al.[18] reported that the salt content of an entire dry-cured ham at the end of the elaboration process correlated well to the CT values obtained from a 10 mm slice during the process. In this study, the potential utility of line profiles as a promising tool for the analysis of salt distribution and dehydration within a ham was confirmed. To the authors' knowledge, there is only a preliminary study[14] in which a_w prediction at the initial stages of the process by means of CT is reported.

The aim of this study was to develop different CT analytical tools for the nondestructive evaluation of salt content, water content, and a_w and their distribution in dry-cured hams during the elaboration process and apply them to two case studies.

MATERIALS AND METHODS

Ham Model Samples. Regression models that could be applied throughout the whole elaboration process were developed with chemical and CT attenuation data of the *Semimembranosus* (SM) and *Biceps femoris* (BF) muscles from hams comprising the entire elaboration process. The data were taken from previous studies: 40 SM and 21 BF at the initial stages of the process;[12] 60 SM and 30 BF at the initial and medium stages of the process;[14] and 50 SM and 50 BF at the final stages.[13]

Case Studies. Two batches of 18 hams were selected from commercial slaughterhouses. They were elaborated at two different dry-cured ham industries following two different salting procedures: pile salting (PSal) and tumbler salting (TSal) procedure, in which standard (SS) and reduced (SR) salting levels were used. Homogeneous sets of hams in terms of weight and pH were used for each elaboration procedure. Ham average weights were 10.65 ± 0.26 for PSal hams and 12.42 ± 0.1 kg for TSal hams, whereas the pH in the SM muscle at 24 h post-mortem (pH_{24}) ranged between 5.6 and 5.7 in hams from both salting procedures.

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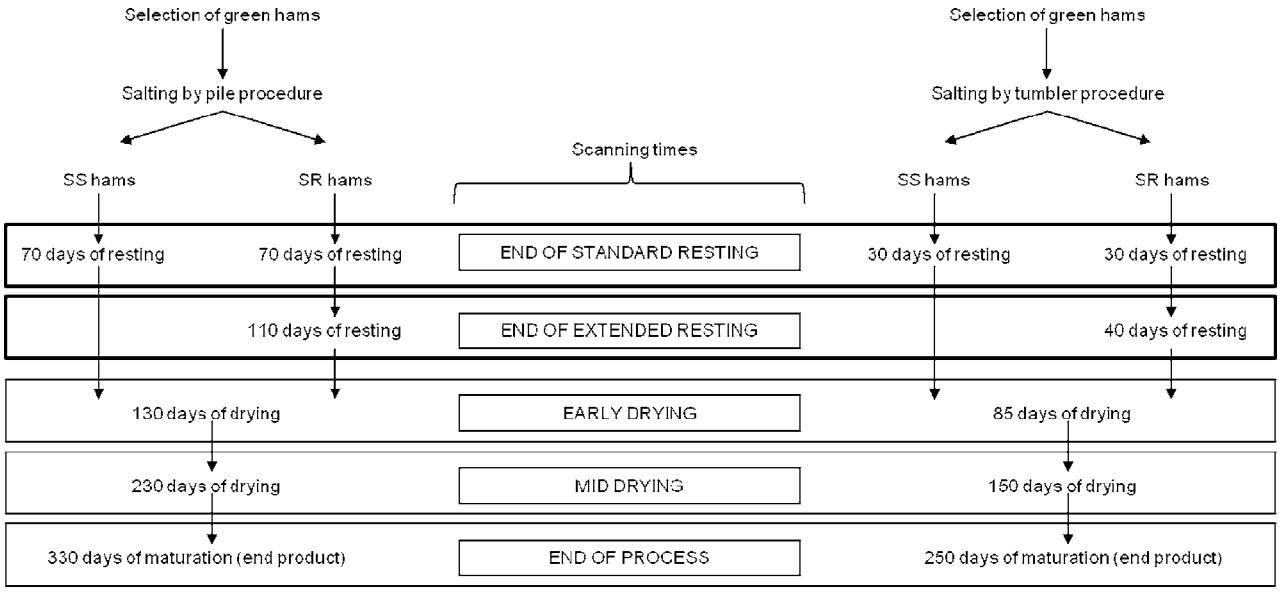

Figure 1. Comparison of pile (PSal) and tumbler (TSal) elaboration procedures for SS and SR hams. Scanning times are shown.

For the PSal procedure, 18 hams were obtained from 9 carcasses and were manually rubbed with the following mixture (g/kg of raw ham): 0.15 of KNO_3, 0.15 of $NaNO_2$, 1.0 of dextrose, 0.5 of ascorbic acid, and 10 of NaCl. Nine hams were pile salted using a SS process (18 days), whereas the rest were salted for less time (5 days) until a reduction of 35% of the standard salt content (SR) was reached.[4] After salting, the hams were washed in cold water and hung in a cold room at 3 °C to rest. The relative humidity (RH) inside the cold room was 75−80%, and the temperature was progressively increased (from 10 to 20 °C) until the end of process. The process was stopped when a total weight loss of 34% was achieved.

For the TSal procedure, 18 hams were salted with a tumbler with the following mixture (g/kg of raw ham): 40 of grained NaCl, 15 of fine NaCl, 1.0 of dextrose, 150 ppm of NO_3, and 150 ppm of NO_2. The hams remained at low temperature (2 °C) and 75−80% RH inside a container for 4 weeks (28 days) with the salting mixture and the exudate from the hams. Nine hams were salted using the standard salting mixture (SS), whereas the rest were salted using 30% less NaCl (SR). To ensure uniform distribution of salt inside the container, hams were rotated inside the container once a week. Following this, hams were washed in cold water and hung at 10−30 °C and 70% RH. The temperature of the drying room was increased 1 °C per week until the end of the process (30% total weight loss).

CT Scanning Conditions. CT scanning of 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 and 120 kV, 250 mAs, 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 because it gives a high-contrast spatial resolution in samples containing soft tissue (lean and fat) and mineral phases (mainly NaCl). In this study, each pixel had an area of 0.81 mm^2 and a CT value expressed in Hounsfield units (HU). Matrices of values obtained from the scans were saved and retrieved with Matlab for further automated analysis using developed scripts.

From all of the hams, 10 mm thick tomograms were obtained at 10 cm from the aitch bone in the distal direction (at the widest part of the ham) (Figure 2). BF and SM muscles were present in all scanned volumes. To develop predictive models,[12−14] two or three consecutive tomograms were taken to obtain a sufficient quantity sample for the chemical analysis. Mean CT values from each region of interest (ROI) of the consecutive tomograms were calculated, obtaining a mean CT attenuation value at 80 and 120 kV (HU_{80} and HU_{120}, respectively). The above samples showed important chemical variations with respect to salt and water contents and a_w. Only one tomogram was needed for the prediction in the industrial case studies, but the hams were scanned several times during the process. To scan the hams in the same position, two metallic benchmarks (2 mm diameter) were placed inside the bone of the hams as a reference. The hams were scanned at the end of the resting period, at the early stage of drying, at the mid stage of drying, and at the end of the process. Nevertheless, because of the differences between case studies (PSal and TSal procedures) and salting processes (SS and SR), scanning times were specific in each case (Figure 1). In the case of the SR salting process, the hams were scanned several times during the resting period until reaching the same salt level as SS hams.

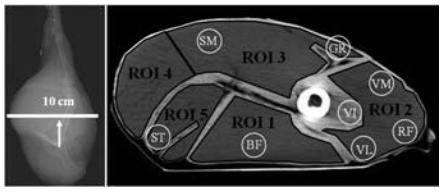

Figure 2. CT scan location (A) and the cross-sectional CT image (tomogram) obtained in which different muscles can be distinguished (B). The five selected ROIs are also indicated. SM, *Semimembranosus* muscle; GR, *Gracilis* muscle; VM, *vastus medialis* muscle; VI, *Vastus intermedius* muscle; VL, *Vastus lateralis* muscle; RF, *Rectus femoris* muscle; BF, *Biceps femoris* muscle; ST, *Semitendinosus* muscle.

Tools for the Analysis of CT Data. Matlab scripts written in-house (MATLAB, ver. 7.7.0, The Mathworks Inc., Natick, MA) were developed to analyze the matrices of values obtained from the scans. The shape and composition of the hams varied greatly during the dry-cured ham elaboration process, so the segmentation had to be especially robust for the extraction of data features to be consistent. In brief, matrices of attenuation values acquired at two different CT energies (80 and 120 kV) were converted to matrices of salt and water contents and a_w using the improved models. Because these models could not predict these parameters in the fat tissue, CT tomograms were segmented by excluding pixels belonging to the fatty areas (subcutaneous fat, intermuscular fat, and the main streaks from the intramuscular fat) and the bone. The resulting matrices contained values only for areas that were segmented as lean.

Another Matlab script developed from matrices of attenuation values acquired at 80 kV was used to assess the percentage of subcutaneous fat tissue.

Distribution Diagrams. Two-dimensional distribution diagrams of salt and water contents and a_w were obtained for the whole slice

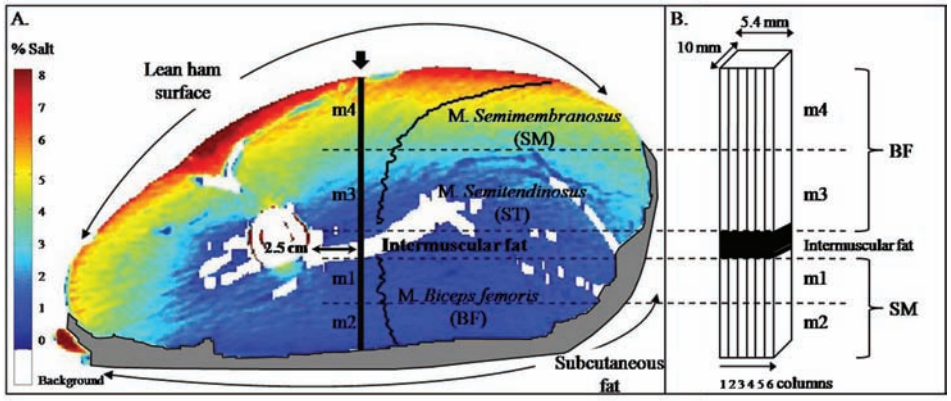

Figure 3. (A) Example of a distribution diagram and a line profile of salt content (%) in a dry-cured ham. Line profile is marked with an arrow. Subcutaneous fat (depicted in gray) is indicated by a line for better comprehension. (B) Detail of a line profile.

(Figure 3), showing the chemical composition and spatial distribution for each compound. Specific RGB color scales were used for convenience. Due to the fact that the three compounds cannot be estimated in fat tissue, areas representing fat are depicted in white.

Regions of Interest Mean Values. ROIs were manually selected on tomograms, and values were retrieved (Figure 2). From each ROI and sampling time, the mean values and standard deviation of salt and water contents and a_w were obtained.

Line Profiles. Line profiles are defined as a one-dimensional graphic representation of salt and water contents and a_w along a specific line of the ham (Figure 3). These line profiles, obtained at different moments during the process, illustrate the variation of salt and water contents and a_w during manufacturing time, as well as morphological changes such as the retraction of the ham. Line profiles are the average values of six columns of the matrices obtained for generating distribution diagrams. Selected columns are located adjacent to the femoral bone and separated at a distance of 2.5 cm from it, in the direction of the *Semitendinosus* muscle (ST). They represent a parallelogram with 10.0 mm depth, 5.4 mm width, and the length corresponding to the thickness of the ham. In these line profiles, two different areas separated by the region of the intermuscular fat can be distinguished, corresponding to the SM and BF muscles. To facilitate the comparison of different line profiles, they were aligned to the intermuscular fat region (Figure 3).

From each line profile different mean values can be calculated to obtain more detailed and comparative information about ham composition: m_1, m_2, m_3, and m_4 (Figure 3). m_3 and m_4 were located in the SM muscle, whereas m_1 and m_2 were located in the BF muscle.

Statistical Analysis. The SAS package (SAS Institute Inc., Cary, NC, 2001) was used to obtain improved predictive models and to test differences between ROIs at different scanning days or salting level (SS and SR) for each salting procedure (PSal and TSal).

Regression Models. Regression models for salt content, water content, and a_w values on HU_{80} and HU_{120} (prediction models) were obtained using the REG procedure from the SAS package. Independent variables of the model were selected by the Stepwise method. Significant levels to enter and keep the dependent variables in the model were $P = 0.25$ and $P = 0.10$, respectively.

Regression models were validated by a cross-validation with stratified segmentation. The stratified segmentation, when all of the data were considered, produced 12 groups of 20−21 samples in the case of salt and water contents and 10 groups of 19 samples in the case of a_w.

The predictability of such models can be given by the coefficient of determination (R^2, the root mean square error of prediction (RMSEC) value ,and the root mean square error of cross-validation (RMSECV) as was described in Santos-Garcés et al.[13]

Differences between ROIs, Scanning Days, and Salting Levels. To establish differences between ROIs for a given scanning time and salting level, a simple ANOVA was performed. When differences between ROIs within scanning times and salting levels were tested, the model included ROI and ham as fixed effects. When differences between scanning times within ROIs and salting levels were tested, the model included ham and scanning time as fixed effects. When differences between salting levels within ROIs and scanning times were tested, the model included salting level as fixed effect. The least significance difference (LSD) test was applied to compare the means, with significance established at $P = 0.05$.

RESULTS AND DISCUSSION

Improved Predictive Models for Salt and Water Contents and a_w. The new models satisfactorily predicted salt content (RMSECV = 0.393%), water content (RMSECV = 1.751%), and a_w (RMSECV = 0.008%) using two voltages (80 and 120 kV) (Table 1), although a_w could be estimated with the same accuracy with only one energy (80 kV) (RMSECV = 0.008%), during the entire elaboration process (Table 1). Fat content produced an overestimation in the predictions of water content and a_w, whereas no effect was evident for salt content prediction (results not shown). Similar results were found when using models developed at the initial[12,14] and final stages of the process.[13] Because the average attenuation value of a specific region depends on its average composition (in terms of salt, water, fat, and proteins contents), different percentages of these compounds could result in the same attenuation values. Because of this, and because fat produces low attenuation values, fatty samples can produce an important decrease in the average attenuation value, which could be interpreted as higher water content than the true average content. The correction of the predictions as a function of fat content, by including fat information in the models, could improve these predictions. Because the new models developed contained a wide range of data that includes samples from the initial to the final stages of the process, RMSECV values for salt content and a_w were

Table 1. Predictive Models for Salt and Water Contents and a_w Obtained from the Improvement of the CT Calibration (SM and BF Samples) Using Two Voltages (80 and 120 kV)

prediction model	n	RMSEC	R^2	RMSECV
salt (%) = 0.17 + 0.1926(HU_{80}) − 0.1889(HU_{120})	251	0.396	0.960	0.393
water (%) = 90.0 + 0.575(HU_{80}) − 0.844(HU_{120})	251	1.762	0.912	1.751
a_w = 1.0387 − 0.00037(HU_{80}) − 0.00027(HU_{120})	190	0.008	0.906	0.008

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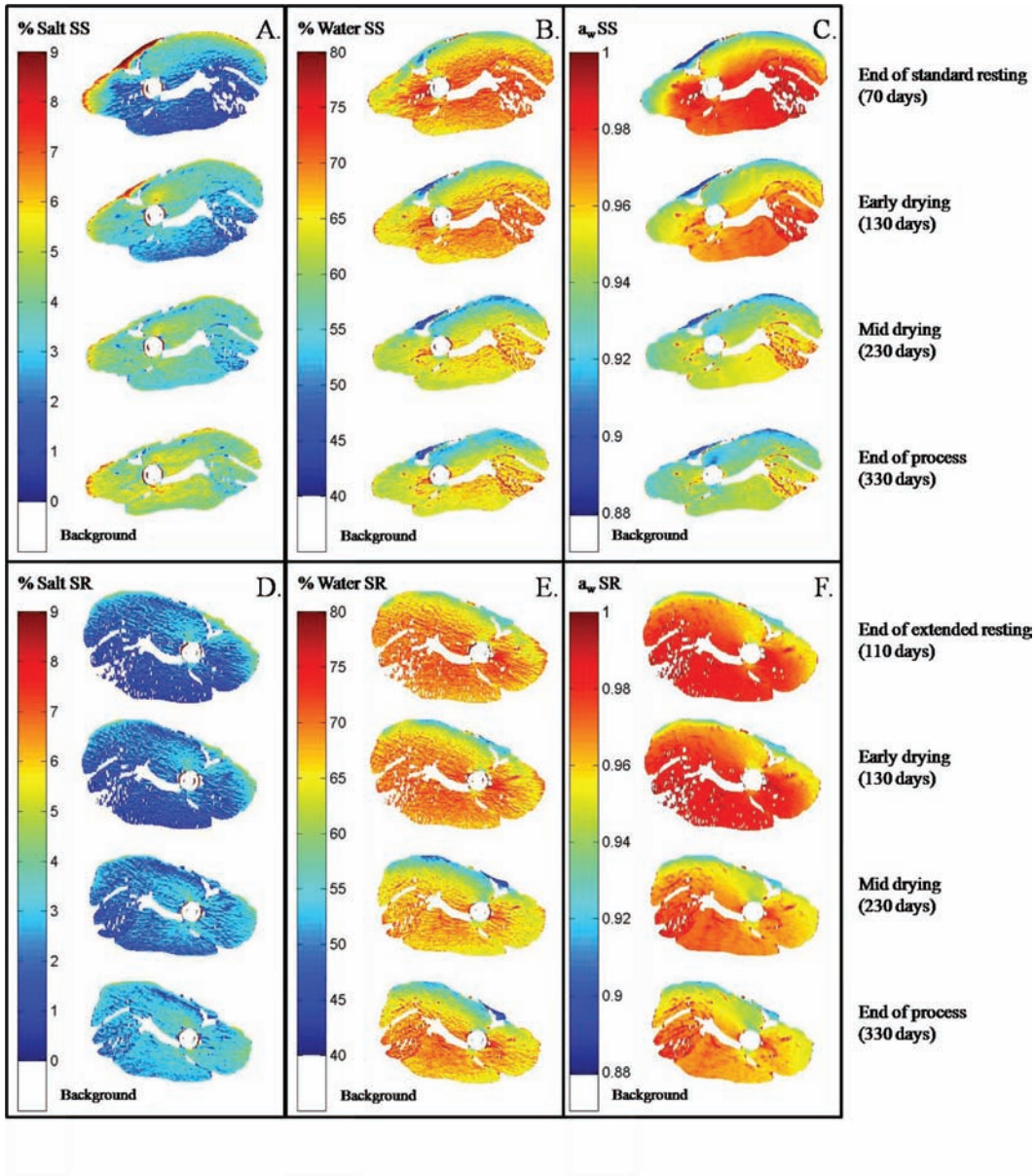

Figure 4. Example of salt and water contents and a_w distribution diagrams of a representative SS and SR ham using pile salting procedure (PSal), obtained at different scanning times during the elaboration process.

higher than the ones obtained specifically for the initial ($RMSECV_{salt}$ = 0.30% and $RMSECV_{aw}$ = 0.0048%) or final stages ($RMSECV_{salt}$ = 0.279% and $RMSECV_{aw}$ = 0.0075%). The new models are useful for studying the whole elaboration process of the same ham. Moreover, the use of only two voltages reduces the cost of CT analysis in comparison to the previous models, which used three voltages (80, 120, and 140 kV).[13] These findings are in agreement with ref 11, in which two (or three) voltages of 80 and 110 (and 130 kV) were recommended.

Usefulness of CT Analytical Tools. Distribution diagrams can be used to extract desired product information. To obtain additional valuable and quantitative information, several ROIs can be acquired from these distribution diagrams. Because predictive models are well suited for the estimation of salt and water contents and a_w, their implementation for the estimation of these parameters in different ROIs, scanning times, and salting levels can be carried out.

Line profiles can also be obtained from distribution diagrams and give quantitative information at a fixed point and as a continuous line (Figure 5). Line profiles allow deep penetration of the ham slice, which is necessary when the chemical composition of the sample surface does not correlate closely with the average of the whole slice or with other regions of the ham. Thus, some regions can be emphasized, whereas others can be omitted. For example, m_1 corresponds to the most internal part of the BF muscle in which microbiological hazards or sensory defects are more prone to occur (Figure 3). Determination of the resting period time can be defined as a function of the salt content, water content, or a_w in the internal part of the BF muscle, as well as provide information to optimize the elaboration process. Information obtained from line profiles, while manufacturing is in progress, may also permit the estimation of diffusion coefficients for salt and water in dry-cured ham as a function of time and distance.[19,20] The relationship between salt and water contents and their

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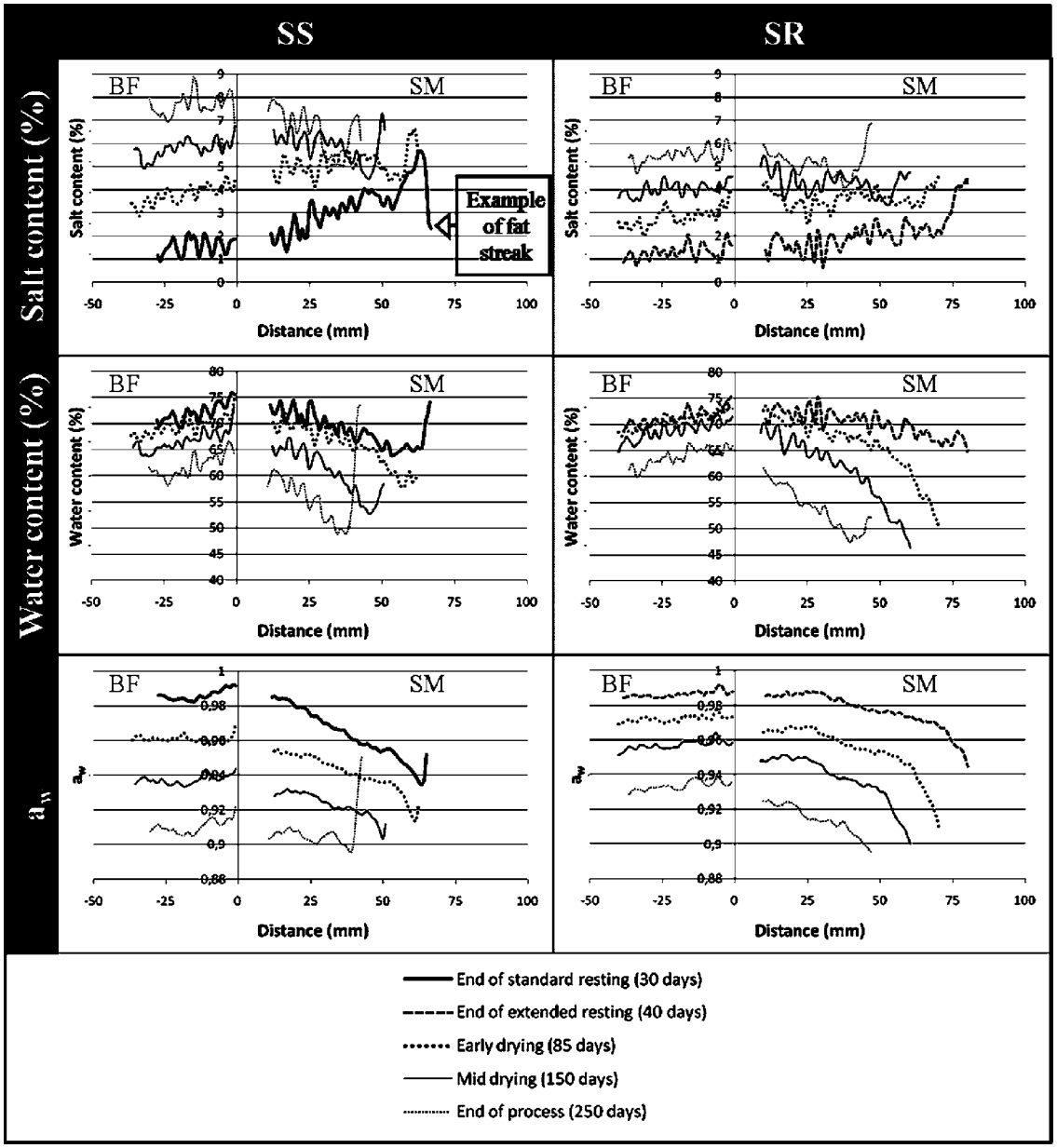

Figure 5. Example of salt and water contents and a_w line profiles from a representative SS and SR ham salted using a tumbler procedure (TSal), obtained at different scanning times during the elaboration process.

diffusivities can also be evaluated. Measuring salt and water diffusivity in relation to water content could be useful for modeling food industry operations such as the dry-cured ham elaboration process for which the internal transfer of water (refrigeration, drying, aging, brining, storage, etc.) is a key factor for both process efficiency and product quality. The estimation of the continuous variation of these parameters is of special interest to simulate salt penetration and water loss in a model system. Although information from matrices was improved by removing fat tissue (by fat segmentation) to reduce data noise, some fat streaks can appear at the beginning of the line profiles (in the SM muscle) (Figure 5) between the gracilis (GC) and SM muscles (Figure 4). The segmentation was not efficient enough because salty lean meat tissues and salty fat tissues could not be easily distinguished. Salt present in fat tissue increased X-ray attenuation (due to the high density of NaCl ions), and therefore the fat marbling could not be properly differentiated from the lean tissue.

Application in the Case Studies. In this study, five ROIs were selected to obtain information regarding the variation of salt and water contents and a_w of different regions of a slice from each ham throughout the elaboration process (Figure 1). ROI 1 contained the BF muscle; ROI 2 included a group of different muscles such as the *Rectus femoris* (RF), the *Vastus lateralis* (VL), the *Vastus medialis* (VM), and the *Vastus intermedius* (VI); ROI 3 included the GC muscle and a part of the SM muscle; ROI 4 contained the rest of the SM muscle; and ROI 5 contained the ST muscle (Figure 2). Tables 2 and 3 show the salt and water contents and a_w values for the PSal and TSal procedures, respectively, as a particular example of ROI mean value utility. Expected results along the whole elaboration process were obtained. During the elaboration process salt diffuses to less salty areas through the lean ham surface (SM muscle, ROI 3, and ROI 4) and the regions in which subcutaneous fat is thin, which is also shown in the distribution diagrams (Figure 4) and line profiles (Figure 5). Subcutaneous

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Table 2. Example of ROI Salt and Water Contents and a_w Mean Values and Standard Deviation of Salt and Water Contents from SS and SR Hams Salted by Pile Procedure (PSal) (n = 9)[a]

			ROI 1		ROI 2		ROI 3		ROI 4	
salt group	scanning time	day of process	mean	SD	mean	SD	mean	SD	mean	SD
					Salt Content (%)					
SS	end of standard resting	70	1.53b,w,α	0.52	3.51a,w,α	0.41	3.61a,x,α	0.32	3.61a,x,α	0.43
	early drying	130	2.48c,x,α	0.83	3.98a,x,α	0.26	3.85a,b,y,α	0.26	3.66b,x,y,α	0.44
	mid drying	230	3.65c,y,α	1.23	4.22a,y,α	0.44	3.76b,c,x,y,α	0.51	3.86b,y,α	0.58
	end of process	330	4.67b,z,α	1.55	4.90a,z,α	0.49	4.22c,z,α	0.56	4.47b,z,α	0.63
SR	end of extended resting	110	1.27c,w,β	0.43	2.50a,x,β	0.38	2.35a,b,x,β	0.08	2.29b,x,β	0.20
	early drying	130	1.44c,x,β	0.48	2.57a,x,β	0.38	2.37b,x,β	0.11	2.29b,x,β	0.23
	mid drying	230	2.46b,y,β	0.87	3.00a,y,β	0.45	2.59b,y,β	0.44	2.58b,y,β	0.40
	end of process	330	3.14b,z,β	1.02	3.58a,z,β	0.34	2.98c,z,	0.24	3.16b,z,β	0.39
					Water Content (%)					
SS	end of standard resting	70	69.32a,z	0.75	66.48c,z,α	0.51	65.39d,z	0.54	67.51b,z	0.79
	early drying	130	68.46a,y,α	0.69	65.90c,z,α	0.64	63.21d,y,α	0.77	66.81b,y,α	1.26
	mid drying	230	64.75a,w,α	1.17	62.51b,y,α	1.49	58.47c,xα	1.72	62.08b,x,α	1.69
	end of process	330	65.13a,w,α	1.31	62.60b,y,α	1.49	57.67d,w,α	1.69	61.35c,w,α	1.90
SR	end of extended resting	110	69.46a,z	0.25	68.35b,z,β	0.75	65.51c,z	0.63	68.31b,z	0.96
	early drying	130	69.29a,z,β	0.19	68.20b,z,β	0.71	65.02c,y,β	0.76	68.03b,z,β	0.96
	mid drying	230	66.73a,x,β	0.57	65.01b,x,β	1.03	60.44c,x,β	1.39	64.29b,y,β	1.22
	end of process	330	67.57a,y,β	0.55	65.56b,y,β	1.07	60.29d,x,β	1.30	63.76c,y,β	1.57
					a_w					
SS	end of standard resting	70	0.980a,z,α	0.003	0.957b,z,α	0.004	0.953c,z,α	0.003	0.958b,z,α	0.005
	early drying	130	0.970a,y,α	0.004	0.951c,y,α	0.003	0.946d,y,α	0.004	0.956b,z,α	0.005
	mid drying	230	0.951a,x,α	0.006	0.941b,x,α	0.007	0.936c,x,α	0.008	0.944b,y,α	0.007
	end of process	330	0.944a,w,α	0.007	0.936b,w,α	0.007	0.930c,w,α	0.008	0.937b,x,α	0.008
SR	end of extended resting	110	0.983a,z,β	0.001	0.970b,z,β	0.004	0.964c,z,β	0.001	0.971b,z,β	0.003
	early drying	130	0.981a,z,β	0.002	0.969b,z,β	0.004	0.963c,z,β	0.002	0.971b,z,β	0.003
	mid drying	230	0.966a,y,β	0.005	0.958b,y,β	0.006	0.951c,y,β	0.006	0.960b,y,β	0.005
	end of process	330	0.962a,x,β	0.003	0.954b,x,β	0.005	0.947c,x,β	0.004	0.953c,z,β	0.006

[a]Means within a row without a common letter (a–d) are significantly different (P < 0.05). Means within a column in the same group without a common letter (w–z) are significantly different (P < 0.05). Means within a column in the same sampling time for SS and SR hams without a common letter (α, β)are significantly different (P < 0.05).

fat and inter- and intramuscular fat represent a barrier for salt uptake[15,21,22] and water loss (mainly in the BF muscle). For this reason, at the initial stages of the process, higher salt content values were achieved in the external part of the ham, facing the open surface without any fat layer protection (SM muscle, ROI 3, and ROI 4) than in the inner areas (BF muscle, ROI 1).[23] In contrast, the BF muscle achieves the highest salt content at the end of the process (Table 3 and Figure 5), which can be explained by the natural tendency of the salt content/water content ratio to equilibrate between different zones of the ham during the process.[23] In most cases, significant differences (P < 0.05) between the same ROI at different scanning times were observed in all the ROIs for both PSal and TSal procedures (Tables 2 and 3). As expected, a_w values of the hams surface decreased significantly as the relative humidity of drying air in the storage room decreased during the elaboration process. Nevertheless, at the end of the manufacturing process, salt content was homogeneous in all of the ROIs of the slice, including ROI 1. Although five ROIs were initially selected from each scan, results from the ST muscle (which corresponds to ROI 5) were not presented because of the prediction problems and low consistency of the models in this muscle, which has the highest level of intramuscular fat.

As was reported before, morphological differences between SS and SR hams and retraction can be observed throughout the elaboration process, such as a reduction of the size of the ham section (Figure 4) or the shortening of line profile total length (Figure 5), both facts due to the loss of water.

In this study, line profiles penetrated the length of the ham slice from the lean surface of the ham (SM) to the subcutaneous fat area (BF muscle). Because m_1 shows the amount of salt and water contents and a_w present in the most internal part of the BF muscle, m_1 values can be used to accurately determine the length of the resting period (stabilization stage) when salt content is reduced. For these case studies, Tables 4 and 5 show m_1 values for SS and SR hams from the PSal and TSal procedures, respectively. In the case of PSal, significant differences between SS hams and SR hams for salt content were obtained at the end of the standard resting period (P < 0.05). Due to the fact that insufficient salt content in the most internal part of the hams (mainly BF muscle) can produce microbiological hazards,[8,9,24] the resting period of SR hams was extended until the same salt content as in SS hams at the end of the standard resting period was obtained. Therefore, the optimization of the resting period length using CT can provide reduced-salt hams as stable as SS hams from a microbiological point of view.

When the two studied elaboration procedures (PSal and TSal) were compared, differences in terms of salt content were observed due to the length of each salting process. PSal hams were kept covered with salt for 18 days (SS hams) or 5 days (SR hams), whereas hams from TSal were all submerged in brine for 28 days. In addition, high percentages of subcutaneous

Table 3. Example of ROIs Salt and Water Contents and a_w Mean Values and Standard Deviation of Salt and Water Contents from SS and SR Hams Salted by the Tumbler Procedure (TSal) (n = 9)[a]

			ROI 1		ROI 2		ROI 3		ROI 4	
salt group	scanning time	day of process	mean	SD	mean	SD	mean	SD	mean	SD
					Salt Content (%)					
SS	end of standard resting	30	1.22d,w	0.41	3.35b,w,α	0.55	2.84c,w,α	0.49	3.73a,x,α	0.46
	early drying	85	3.22c,x,α	1.08	4.80a,x,α	0.52	4.39b,x,α	0.42	4.56b,y,α	0.47
	mid drying	150	4.74c,y,α	1.60	5.40a,y,α	0.66	5.03b,y,α	0.53	4.89b,c,y,α	0.59
	end of process	250	6.49a,z,α	2.17	6.44a,z,α	0.77	5.79b,z,α	0.69	5.47c,z,α	0.75
SR	end of extended resting	40	1.24c,w	0.44	2.70a,w,β	0.20	2.05b,w,β	0.17	2.66a,x,β	0.44
	early drying	85	2.30c,x,β	0.75	3.34a,x,β	0.22	3.03b,x,β	0.25	2.99b,y,β	0.34
	mid drying	150	3.17c,y,β	1.05	3.80a,y,β	0.27	3.42b,y,β	0.28	3.17c,y,β	0.21
	end of process	250	4.35a,z,β	1.45	4.58a,z,β	0.44	3.99b,z,β	0.34	3.69c,x,β	0.26
					Water Content (%)					
SS	end of standard resting	30	71.46a,z,α	0.43	70.61b,z	0.79	69.22c,z	1.03	69.44c,z	0.59
	early drying	85	69.48a,y,α	0.73	68.59a,y	1.46	66.33b,y	0.97	66.77b,y	1.82
	mid drying	150	66.59a,x,α	1.10	64.92b,x,α	2.32	61.49c,x	1.38	61.69c,x	2.52
	end of process	250	62.29a,w,α	1.40	60.70a,w	2.71	56.28b,w	1.31	57.09b,w	2.46
SR	end of extended resting	40	70.51a,z,β	0.24	70.62a,z	0.49	69.33c,z	0.60	69.91c,z	0.92
	early drying	85	70.22a,z,β	0.56	69.75a,y	0.75	66.81c,y	1.07	67.72c,y	1.86
	mid drying	150	68.48a,y,β	0.74	66.88b,x,β	1.31	63.10c,x	1.94	63.89c,x	3.02
	end of process	250	64.12a,x,β	1.04	62.16b,w	1.76	57.39d,w	2.73	59.09c,w	3.41
					a_w					
SS	end of standard resting	30	0.988 a,z	0.002	0.967 b,z,α	0.006	0.969 b,z,α	0.006	0.961c,z,α	0.005
	early drying	85	0.966a,y,α	0.005	0.950b,y,α	0.007	0.949b,y,α	0.006	0.948b,y,α	0.008
	mid drying	150	0.946a,x,α	0.008	0.937b,x,α	0.010	0.932c,x,α	0.008	0.934b,c,x,α	0.010
	end of process	250	0.921a,w,α	0.010	0.918a,b,w,α	0.011	0.914b,w,α	0.008	0.918a,w,α	0.009
SR	end of extended resting	40	0.985a,z	0.002	0.973c,z,β	0.002	0.976b,z,β	0.003	0.972c,z,β	0.005
	early drying	85	0.976a,y,β	0.003	0.965b,y,β	0.003	0.961c,y,β	0.004	0.964b,c,y,β	0.007
	mid drying	150	0.964a,x,β	0.004	0.955b,x,β	0.005	0.950c,x,β	0.007	0.954b,y,β	0.008
	end of process	250	0.944a,w,β	0.006	0.938b,w,β	0.007	0.932c,w,β	0.009	0.938b,w,β	0.008

[a]Means within a row without a common letter (a−d) are significantly different (P < 0.05). Means within a column in the same group without a common letter (w−z) are significantly different (P < 0.05). Means within a column in the same sampling time for SS and SR hams without a common letter (α, β) are significantly different (P < 0.05).

Table 4. Example of m_1 Mean Values for Salt and Water Contents and a_w from SS and SR Hams Salted by the PSal Procedure (n = 9)[a]

		end of standard resting 70 days		end of extended resting 110 days		early drying 130 days		mid drying 230 days		end of process 330 days	
measured variable	salt group	m_1	SD	m_1	SD	m_1	SD	m_1	SD	m_1	SD
salt (%)	SS	1.93d,z	0.15			3.02c,z	0.22	3.02c,z	0.42	5.06a,z	0.49
	SR	1.36d,y	0.17	1.69c[b]	0.19	1.84c,y	0.19	1.84c,y	0.47	3.39a,y	0.22
water (%)	SS	71.73a,z	0.86			70.61b,z	0.71	70.61b,z	0.80	67.41c,z	1.17
	SR	72.49a,z	0.62	71.52b	0.60	71.20b,z	0.59	71.20b,z	0.82	69.79c,z	0.95
a_w	SS	0.982a,z	0.002			0.970b,z	0.003	0.970b,z	0.005	0.945d,z	0.006
	SR	0.989a,y	0.002	0.984b	0.002	0.982b,y	0.002	0.982b,y	0.006	0.965d,y	0.004

[a]Means within a row without a common letter (a−d) are significantly different (P < 0.05). [y,z]Means within a column without a common letter (y, z) are significantly different (P < 0.05). [b]The mean of the SR salt group at the end of extended resting is significantly different (P < 0.05) from the mean of the SS salt group at the end of standard resting.

fat content were obtained for PSal hams, and it is known that subcutaneous fat has a retarding effect on salt diffusion[17] because it acts as a barrier for salt uptake.[15,21,22] For these two reasons, TSal hams achieved higher salt content than PSal hams.

Predicted a_w values in SR hams in both case studies (PSal and TSal) at the early drying stage are in agreement with the analytical measurements obtained in fresh hams by Grau et al.[25] a_w values were lower in the SM (ROI 3 and ROI 4) than in the

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Table 5. Example of m_1 Mean Values for Salt and Water Contents and a_w from SS and SR Hams Salted by the TSal Procedure (n = 9)[a]

		end of standard resting 30 days		end of extended resting 40 days		early drying 85 days		mid drying 150 days		end of process 250 days	
measured variable	salt group	m_1	SD	m_1	SD	m_1	SD	m_1	SD	m_1	SD
salt (%)	SS	1.58d,z	0.16			3.61c,z	0.33	5.06b,z	0.58	6.68a,z	0.74
	SR	1.40d,y	0.17	1.42d	0.19	2.66c,y	0.21	3.47b,y	0.37	4.56a,y	0.48
water (%)	SS	73.30a,z	0.59			71.36b,z	0.89	68.34c,z	1.19	63.92d,z	1.40
	SR	72.94a,z	0.82	72.20a[b]	0.69	72.09a,y	0.45	70.88b,y	1.54	66.05c,y	1.47
a_w	SS	0.989a,z	0.002			0.967b,z	0.005	0.947c,z	0.007	0.923d,z	0.009
	SR	0.989a,z	0.003	0.988a	0.003	0.977b,y	0.002	0.967c,y	0.006	0.947d,y	0.007

[a]Means within a row without a common letter (a–d) are significantly different ($P < 0.05$). Means within a column without a common letter (y, z) are significantly different ($P < 0.05$). [b]The mean of the SR salt group at the end of extended resting is significantly different ($P < 0.05$) from the mean of the SS salt group at the end of standard resting.

BF muscle (ROI 1) (Tables 3 and 4), as expected.[22,25−28] The upper a_w values were also obtained in the BF muscle of the fattiest hams (TSal) in agreement with Grau et al.[25] Therefore, the fat concentration in the BF muscle plus the presence of the biggest subcutaneous fat hurdle[15,17,21,22] was responsible for a lower water diffusion rate toward the outside of fatty hams[29] during the salting, resting, and drying stages.

Conclusions. CT analytical tools are useful for characterizing salt and water contents and a_w distribution in dry-cured ham during the elaboration process in different research ways. Subcutaneous fat percentage can also be determined. Information obtained can be applied in case studies for monitoring industrial manufacturing processes, which could help in the reduction of the operating costs and maximize product quality. Nevertheless, the main drawbacks of the method are the disturbance that fat produces in water content and a_w predictions and also the high cost of CT analysis, which slow its use as an online system. Further studies focused toward the nondestructive determination of fat content are needed to monitor the fattiest zones of dry-cured hams.

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