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MRI-aided texture analyses of compressed meat products

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ABSTRACT

Viscoelastic properties of food products can already be assessed by conventional (non-imaging) methods, such as compression-recovery creep (CRC), texture property analysis (TPA) and stress-relaxation (SR) methods. In the study, an alternative to these methods based on MRI of samples in a compression cell is proposed. Different commercial meat products were subjected to two different compression protocols. The first (protocol P1) was designed to mimic a CRC experiment and the second (protocol P2) was based on application of three different constant pressures (0, 160, 400 kPa). The samples were imaged either by consecutive 1D MR intensity profiles (protocol P1) or by 3D T_2 mapping (protocol P2). Compression-induced samples changes were characterized by creep compliance obtained from the 1D profiles, while the T_2 maps were analyzed by using first- and second-order statistical texture feature analyses. The approach enabled spatially-resolved assessment of viscoelastic properties and compression-induced structural changes of the examined samples.

1. Introduction

Food industry produces a wide range of meat products representing a large share in global food market. The products differ with respect to the origin of raw material, biochemical composition and processing protocol. As a result of the interplay between these factors, the meat products differ also by the structure and texture properties that both play a crucial role in consumer acceptability (Morales et al., 2007). Therefore, standardized methods were developed in order to determine structural and textural traits of meat products. Evaluation of textural traits by sensory analysis could be slow and laborious, thus instrumental texture analyses are commonly performed in parallel for a complementary determination of meat product traits (Benedini et al., 2012; Meullenet et al., 1998). Most established techniques for characterization of meat products are texture profile analysis (TPA) (Zamri et al., 2006) and stress-relaxation (SR) experiments (Andres et al., 2008), in which the examined meat samples are subjected to a predefined strain and then the strain-maintaining force is measured as a function of time. In the last decade, a compression-recovery creep (CRC) method was introduced (Dolz et al., 2008), in particular for determination of viscoelastic behavior of low-oil-content meat emulsions. In the CRC method, the examined sample is subjected to an external stress, while the strain as a function of time is measured. Such viscoelastic responses can be theoretically analyzed by various viscoelastic models (Mainardi and Spada, 2011). This CRC technique was applied also to other, more compact meat products with various levels of meat fragmentation, such as finely, medium or coarsely ground sausages (Dzadz et al., 2015). For emulsion-like systems, a correlation between the TPA and CRC parameters was recently confirmed (Yilmaz et al., 2012).

The compression experiments (TPA, SR and CRC) represent a golden standard for characterization of texture features of food products (Chen and Opara, 2013). However, the experiments yield spatial-averaged parameters, while spatial distribution of structural changes (such as local deformations and possible cracks) induced in the sample during compression are inherently inaccessible by these experiments. Therefore, another, preferably nondestructive, methods are needed to assess these changes. Recently, a novel approach employing visible/near-infrared hyperspectral imaging was efficiently used for determination of spatial distribution of TPA parameters in salmon fillets (Wu et al., 2014). This approach is inherently limited to superficial layers of examined meat samples due to a relatively small penetration depth of visible/near-infrared light, while the sample interior remains inaccessible for the light and thus cannot be characterized.

Magnetic resonance imaging (MRI) was recognized as an

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List of abbreviations

ADC	apparent diffusion coefficient
CRC	compression-recovery creep
FOV	field of view
GLCM	gray-level co-occurrence matrix
iTE	inter echo time
MR	magnetic resonance
MRI	magnetic resonance imaging
NMR	nuclear magnetic resonance
RF	radio frequency
SNR	signal to noise ratio
SR	stress-relaxation
T_1	longitudinal (spin-lattice) NMR relaxation time
T_2	transversal (spin-spin) NMR relaxation time
TE	time to echo
TPA	texture profile analysis
TR	time to repeat

important biophysical method for nondestructive characterization of food products (Damez and Clerjon, 2008). For example, the method was proven useful for determination of water ingress into individual rice kernels during cooking (Mohoric et al., 2009), for determination of pores distributions in cheese (Musse et al., 2014), for a follow-up of dough fermentation (Bonny et al., 2004) and for a dynamical monitoring of dry-cured hams during their processing (Fantazzini et al., 2009). The characterization is based on spatial variations of water-proton density and apparent diffusion coefficient as well as on the intrinsic MR parameters, such as longitudinal (T_1) and transversal (T_2) NMR relaxation times, across the examined sample. Moreover, advanced MRI methods primarily developed for diagnosing various diseases were also efficiently translated to meat science. For example, diffusion-tensor imaging was employed for determination of fiber orientation in beef meat (Renou et al., 2003). Recently, a deformation vector field in beef muscle samples during cooking was determined (Bouhrara et al., 2012). The study proved MRI also a promising method for dynamical monitoring of meat structural changes during the mechanical/thermal processing.

Providing the voxel size is sufficiently small to avoid the partial volume effect, local intensity variations in MR images and MR-parameter maps enable clear visual distinction among differently processed meat samples as well as among different meat regions, e.g., lean meat vs. fat inclusions (Collewet et al., 2005). More detailed characterization of meat products can be obtained by calculating first-order statistical texture features derived from image multidimensional histograms (Bajd et al., 2016). Even better characterization can be obtained by second-order statistical texture feature analysis employing the gray-level co-occurrence matrix (GLCM) method (Cernadas et al., 2005; Shiranita et al., 1998; Wu et al., 2014), which was first introduced by (Haralick et al., 1973). Recently, the GLCM method was efficiently employed for determination of the feeding background effect on texture properties of dry-cured and fresh Iberian ham (Perez-Palacios et al., 2010, 2011). In these studies, discrimination between hams of pigs fattened only with acorns and grass and those fattened with high oleic acid concentrates was confirmed based on second-order statistical texture features of platform-dependent T_1-weighted MR images. In combination with the artificial neural network modelling approach (Zhou and Li, 2007) and the data mining approach (Caballero et al., 2016), MRI was proven efficient for characterization of meat texture and sensory traits.

The aim of this study was to analyze various meat products (plain and cheese-filled poultry frankfurter sausages, smoked and dry-cured pork sausages, and dry-cured hams) during their compression by means of MRI. To this end, the meat samples were compressed to different levels of compression inside a specially designed MR-compatible compression cell. Sample changes were sequentially imaged by 1D profiles during compression and recovery as well as by 3D T_2 mapping in an uncompressed/compressed state. The obtained T_2 maps were analyzed by T_2 histograms and GLCM-derived texture features.

2. Material and methods

2.1. Preparation of meat product samples

Five different meat products, classified in the following groups (G1-G5), were analyzed: plain poultry frankfurter sausage (G1, Pivka, Slovenia), cheese-filled frankfurter sausage (G2, Agricola Italiana Alimentare, Verona, Italy), smoked pork sausage (G3, Mesnine dežele Kranjske, Ljubljana, Slovenia), dry-cured pork sausage (G4, PKK Karlovačka mesna industrija, Karlovac, Croatia) and dry-cured ham (G5) originating from our previous studies (Bajd et al., 2016; Skrlep et al., 2016). From each group, samples with a size of $12 \times 12 \times 27$ mm^3 were dissected from the bulk meat product, in order to fit into an MRI-compatible compression cell with an inner diameter of 20 mm. The sample length of 27 mm was determined by the sensitive region of an MRI probe into which the cell was inserted. At least five samples were analyzed for each sample group.

2.2. MRI-compatible compression cell

The compression cell had a cylindrical shape and was made of a hard plastic material (PE 1000). A 10 ml syringe with a 20 mm diameter piston was inserted into the cell and clamped to the cell housing. The syringe was connected to an external air pressure network with negligible pressure fluctuations via a pressure regulator. The compression force to a sample inside the cell was obtained by adjusting the pressure regulator to a desired pressure of up to 400 ± 10 kPa. The compression cell inserted inside the MRI probe is schematically shown in Fig. 1a.

2.3. Compression protocol

The samples were examined by two different compression protocols (P1 and P2). The compression protocol P1 was designed to mimic a CRC experiment (Fig. 1b). In the protocol, pressure was gradually increasing in one minute intervals from zero to 160 kPa and back to zero in 40 kPa steps (four pressure steps up and four pressure steps down). The pressure intervals were interspersed with one minute intervals of zero-gauge pressure, i.e., each pressure interval was followed by one-minute decompression interval. The final decompression interval was 6.5 min long to enable following the final creep recovery of the sample. By the protocol viscoelastic response of at least three samples of each group was examined. In the compression protocol P2, parallel samples (at least two from each group) were MRI-examined in 3D after their compression to 160 kPa and 400 kPa. With both pressure protocols the pressure changes were instant. The pressure changes were enabled by using incompressible tubes of small volume and the pressure regulator valve that instantly equalized the pressure between the pressure cell and either the external air pressure network (sample compression) or zero-gauge pressure (sample recovery).

2.4. Creep response modelling

Creep behavior of the samples examined by the pressure

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