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Multi-scale characterization of pasta during cooking using microscopy and real-time magnetic resonance imaging

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ABSTRACT

Macroscopic properties of pasta, such as the texture, are formed during cooking by a complex interplay of water and heat with the structuring agents starch and gluten. The impact of the starch-to-gluten ratio on microstructure and water distribution in pasta was analyzed by a multi-scale approach combining magnetic resonance imaging (MRI) and light microscopy. The cooking process and thus the water distribution was monitored non-invasively using ^{1}H MRI in real-time with a temporal resolution of 45 s. Our MRI set-up allowed following the water ingress by imaging the reduction of the uncooked core. The water ingress rate was neither dependent on pasta composition nor on the presence of salt in the cooking media (0.7% NaCl). Starch-rich samples showed a more homogeneous water distribution in the gelatinized zone, which was mirrored in a more homogeneous microstructure. In contrast, gluten-rich samples showed both a heterogeneous water distribution and microstructure. Thus, the gluten content affected local water content in the gelatinized zone but not the water ingress.

1. Introduction

Most consumers determine the quality of cooked pasta based on appearance and texture properties (Marchylo, Dexter, & Malcolmson, 2004). The texture is influenced by the two main components of pasta, starch and gluten. Both components alter the microstructure during the cooking as starch granules swell and disintegrate while gluten polymerizes (Resmini & Pagani, 1983). High protein content and a certain protein composition have been shown to correlate with desired texture parameters such as high firmness and low stickiness (Cubadda, Carcea, Marconi, & Trivisonno, 2007; Marchylo et al., 2004).

Together with starch and gluten content, the ingress and distribution of water are important factors in defining the texture of pasta as well (Horigane et al., 2006). An earlier study suggested that higher protein content results in a slower water ingress into the spaghetti towards the center (Grzybowski & Donnelly, 1977), while others could not observe any differences (Cubadda et al., 2007).

^{1}H magnetic resonance imaging (MRI) is a non-invasive method that spatially resolves the amount and dynamics of water- and macromolecule-protons. ^{1}H MRI has been applied to monitor the water ingress and distribution in pasta and noodle samples at different cooking stages (Bonomi et al., 2012; Horigane et al., 2006; Kojima, Horigane, Nakajima, Yoshida, & Nagasawa, 2004; Lai & Hwang, 2004; McCarthy, Gonzalez, & McCarthy, 2002). In the aforementioned studies, pasta or noodle samples have been cooked for a definite period of time and then removed from the water prior to MRI measurements. However, a more detailed analysis can be obtained from real-time measurements, i.e. acquiring MR images during the cooking. Mohorič et al. (2004) applied this concept to study the slow cooking process of rice kernels. We adapted the aforementioned method to monitor the water ingress and the changes in microstructure in model spaghetti throughout the cooking in real-time with a temporal resolution of 45 s.

This study uses a multi-scale approach investigating the microstructural changes in pasta throughout the cooking dependent on (i) the raw materials used and (ii) the presence of salt in the cooking water. The water ingress was monitored non-invasively with an accuracy of about hundred micrometers in real-time using MRI and was confirmed by polarized light microscopy. MR parameter maps were correlated with light microscopy images on the micrometer scale to characterize

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the extent of raw material transformation and thus the microstructural changes in pasta.

2. Material and methods

2.1. Material

Durum semolina (carbohydrate content 77% (w/w), protein 15% (w/w) of dry matter) was supplied by Lantmännen Cerealia (Malmö, Sweden). Starch (carbohydrate 99% (w/w), protein 0% (w/w) of dry matter) and gluten powder (carbohydrate 8% (w/w), protein 86% (w/w) of dry matter) were supplied by Lantmännen Reppe (Lidköping, Sweden). Starch and gluten were derived from soft wheat. Sodium chloride (NaCl) was purchased in a local supermarket. From here on all concentrations given below are in % (w/w) if not noted differently.

2.2. Pasta production

Spaghetti samples were produced on laboratory-scale with a wide range of starch-to-gluten ratios. The reference sample D100 was made of 100% durum semolina and was comparable in composition to a standard commercial pasta product. For the starch-rich pasta termed S40D60, 40% of the semolina was replaced equally with starch powder. Gluten-rich pasta was produced by replacing 20% (G20D80) and 40% (G40D60) semolina with gluten powder. The carbohydrate and protein contents of the samples were estimated from known compositions and are listed in Table 1.

Batches of 500 g were processed in a lab-scale pasta machine (Edelweiss TR/75C, Italy; machine mixes and extrudes the dough). Water was added to the well-blended dry ingredients to achieve a moisture content of about 33%, while taking the moisture contents of semolina and the powders into account. The ingredients were mixed for 15 min and the dough was extruded through a Teflon-coated die (spaghetti form, 1.5 mm diameter). Spaghetti was hung on racks and placed in a combi steamer oven (CCM, Rational, Germany). The extruded spaghetti rested up to 20 min in ambient conditions due to the handling during and after extrusion. The drying program of Zweifel, Handschin, Escher, and Conde-Petit (2003) was adapted as the oven allowed only limited humidity control. Spaghetti was initially dried for 30 min at 40 °C and then for 120 min at 50 °C. The temperature was step-wise increased to 90 °C within 30 min, kept at this temperature for 30 min, reduced to 50 °C again and kept at 50 °C for 120 min. The relative humidity was kept at the 100% setting of the oven until the last drying step of 120 min where it was reduced to 50%. Spaghetti was stored at room temperature.

2.3. Cooking conditions

Spaghetti samples were cooked for the analyses described in Sections 2.4–2.6 either in distilled water (for MRI experiments ultrapure water, MilliQ, Millipore was used) or distilled water containing 0.7% NaCl (w/v). The salt concentration corresponds to a level commonly chosen for sensory evaluations (Delcour et al., 2000).

2.4. Macroscopic properties

Single strands of spaghetti (25 ± 2 mm in length) were placed in glass tubes containing 10 mL boiling water. The samples were removed after 7.6 min and 13.1 min (corresponding to the time of the eighth and fifteenth image of the MRI series), blotted and weighed. Additionally, the length of the samples was measured before and after cooking using a gauge with an accuracy of 0.02 mm. The weight increase as a measure for water absorption as well as the length increase were determined as the mass and length ratio between the cooked and the dry sample, (W_i/W_{i0}) and (L_i/L_{i0}), respectively.

2.5. Real-time magnetic resonance imaging

MRI experiments were carried out on an 11.7 T Avance II spectrometer (Bruker, Germany) operating at a ^{1}H resonance frequency of 500 MHz. The magnet was fitted with a Bruker MIC-5 microimaging probe giving a maximum gradient strength of 3 T m^{-1} in three orthogonal directions. A 5 mm radiofrequency coil designed to operate at temperatures up to 200 °C (EVT, Bruker, Germany) was used for excitation and detection of the ^{1}H signal. The temperature inside the magnet was controlled by airflow. The heater close to the NMR tube was set to 378 K which yielded a water temperature of 90 °C in the tube after 1 min and reached the set temperature of 99 °C after 3 min. The tube (5 mm outer diameter) was filled 2 cm in height (~400 μL liquid). A glass sphere (3 mm in diameter) was placed at the bottom of the tube to avoid superheating of the cooking water. A 1 cm lengthwise piece of dry pasta was placed 1.5 cm above the bottom of the tube and kept in place with a plastic tube (inner diameter equal to the dry pasta's outer diameter) that was pulled over the top of the pasta piece (further details are depicted in Fig. 1). The prepared tube was placed into the spectrometer at the cooking time zero. Then, the probe was tuned and matched and the signal was put on-resonance. The procedure took about 1 min before the first experiment was initialized. ^{1}H slice selective RARE (rapid acquisition with relaxation enhancement) experiments with a duration of 31 s (plus 16 s for storing data between each experiment) were repeated 15 times giving a total cooking time of 13.5 min. Three slices with a thickness of 1 mm and a gap of 1 mm were acquired using a CPMG sequence (Carr & Purcell, 1954; Meiboom & Gill, 1958) generating 8 echoes, which were spaced by a multiple of 3.66 ms. The field-of-view was set to 15 mm × 5 mm (96 frequency- and 32 phase-encoded points), which gave an in-plane resolution of 0.156 · 0.156 mm^2. One scan was acquired and the repetition time was set to 0.9 s to minimize T_1-weighted signal arising from the pasta, while the cooking water was heavily T_1-weighted and thus had lower signal intensity (Mohorič et al., 2004). The last (16th) experiment lasted 4 min and allowed to estimate additionally T_1 from three repeated experiments with different repetition times t_{Rep}, being 0.9, 1.6 and 5.0 s, respectively.

The acquired complex data was converted to a sequence of 2D images by Fourier transformation and magnitude calculation. The image intensity $I(t)$ as a function of echo time t is given by $I(t) = I_0\exp(-t/T_2)$, where I_0 is the signal intensity at $t = 0$. T_1 was estimated using $I(t_{Rep}) = I_{0T1}[1 - \exp(-t_{Rep}/T_1)]$ where I_{0T1} is the non-weighted signal intensity. For each volume element in the image, the values of I_0, I_{0T1}, T_1 and T_2 were estimated by regressing the equations above onto the experimental

Table 1
Carbohydrate and protein content (% w/w of dry matter) as well as diameter of dried, uncooked spaghetti.

	S40D60	D100	G20D80	G40D60
	40% starch + 60% semolina	100% semolina	20% gluten + 80% semolina	40% gluten + 60% semolina
Carbohydrate	89.5	82.0	67.1	52.9
Protein	08.3	13.9	28.6	43.7
Dry diameter [mm]	1.50 ± 0.05	1.60 ± 0.05	1.65 ± 0.10	1.75 ± 0.10