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 1H 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.

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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).

1H magnetic resonance imaging (MRI) is a non-invasive method that spatially resolves the amount and dynamics of water- and macromolecule-protons. 1H 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...
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 dough was extruded to 99 °C after 3 min. The tube (5 mm outer diameter) was filled 2 cm in height (~400 mL 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. 1H 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; Melboom & 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 mm². One scan was acquired and the repetition time was set to 0.9 s to minimize T₁-weighted signal arising from the pasta, while the cooking water was heavily T₁-weighted and thus had lower signal intensity (Mohoric et al., 2004). The last (16th) experiment lasted 4 min and allowed to estimate additionally T₁ from three repeated experiments with different repetition times texp 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) = I₀ exp(−t/T₂), where I₀ is the signal intensity at t = 0. T₁ was estimated using I(texp) = I₀exp(−texp/T₁) where texp is the non-weighted signal intensity. For each volume element in the image, the values of I₀, I₀exp, T₁ and T₂ 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.

<table>
<thead>
<tr>
<th></th>
<th>S40D60</th>
<th>D100</th>
<th>G20D80</th>
<th>G40D60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrate</td>
<td>89.5</td>
<td>82.0</td>
<td>67.1</td>
<td>52.9</td>
</tr>
<tr>
<td>Protein</td>
<td>08.3</td>
<td>13.9</td>
<td>28.6</td>
<td>45.7</td>
</tr>
<tr>
<td>Dry diameter [mm]</td>
<td>1.50 ± 0.05</td>
<td>1.60 ± 0.05</td>
<td>1.65 ± 0.10</td>
<td>1.75 ± 0.10</td>
</tr>
</tbody>
</table>

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/W₀) and (L/L₀), 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 1H resonance frequency of 500 MHz. The magnet was fitted with a Bruker MRC-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 1H 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 mL 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. 1H 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; Melboom & 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 mm². One scan was acquired and the repetition time was set to 0.9 s to minimize T₁-weighted signal arising from the pasta, while the cooking water was heavily T₁-weighted and thus had lower signal intensity (Mohoric et al., 2004). The last (16th) experiment lasted 4 min and allowed to estimate additionally T₁ from three repeated experiments with different repetition times texp 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) = I₀exp(−t/T₂), where I₀ is the signal intensity at t = 0. T₁ is estimated using I(texp) = I₀exp(1 - exp(−texp/T₁)) where texp is the non-weighted signal intensity. For each volume element in the image, the values of I₀, I₀exp, T₁ and T₂ were estimated by regressing the equations above onto the experimental
data. The 16th experiment was used to estimate the extent of $T_1$-weighting of $I_0$ by calculating the corrected initial signal intensity $I_{0C}$ as follows $I_0 / (1 - \exp(-t_{\text{Rep}} / T_2))$ for $t_{\text{Rep}} = 0.9$ s. Magnitude noise was treated as described in Steglich et al. (2014) and a threshold value was used to avoid inaccurate MR parameter estimations. The threshold was calculated by creating a histogram of a large number of noise values for all runs, which was then fit to a Rayleigh distribution (Sijbers & den Dekker, 2004) and the value at probability $P = 0.999$ was set as the threshold value.

The inner radius was estimated by creating a mask using 30% of the maximal $I_0$ as a cutoff value (Fig. 1). The signal of the cooking water was cut using 60% of the maximal signal intensity at the first echo time as a cutoff value, as depicted in Fig. 1. The spaghetti-shaped pasta was assumed to be circular and thus the inner radius was estimated by taking the square root of the total amount of pixels of the created mask multiplied by $0.1562 \text{ mm}^2/\pi$. The inner radii were estimated for two out of three slices. The data of the slice closest to the plastic tube holder was discarded because of a deviating trend, which might have been caused by temperature differences or air bubbles. S40D60 was difficult to evaluate as small air bubbles were found at the surface after cooking, which created magnetic susceptibility artifacts.

All processing and fitting were done using Matlab (Mathworks, USA). Based on the set of estimated values of $T_2$, a probability distribution was constructed using the built-in kernel density estimator ksdensity with a Gaussian kernel (Bowman & Azzalini, 1997).

2.6. Light Microscopy

The area of the central uncooked core was determined by polarized light microscopy (Del Nobile et al., 2003). Single spaghetti strands were cooked for fixed times, drained and immediately frozen to $-20$ °C. The samples were then cut to a thickness of 10 µm using a cryostat (Leica, Austria) and slices were analyzed without staining.

Sections of samples cooked for 7.6 min and 13.1 min were addition-ally studied by wide-field bright light microscopy to visualize the microstructure. The samples were stained with Light Green for 30 min as well as with iodine in a Lugol’s solution (2:1) for 30 s. In the resulting images, proteins were stained in green, starch granules in blue/violet, amylose in blue and amylopectin in brown.

All samples were analyzed with an Eclipse Ni-U microscope equipped with a Digital Sight DS-Fi2 camera and processed with the software NIS-Elements BR (all Nikon, Japan). The software function ‘n-points’ circle was used to manually determine the diameter of the uncooked core.

3. Results and discussion

The macroscopic water absorption and microstructure of gluten- and starch-rich spaghetti samples were analyzed for two or three cooking time points while the cooking process was monitored throughout the cooking in real-time with a temporal resolution of 45 s using MRI.

We first discuss the results with regards to the raw material composition followed by the impact of salt.

3.1. Macroscopic properties

The analyzed samples varied in initial dry diameter (1.5–1.7 mm), which has been shown to influence the water absorption rate independent of the raw material used (Cafieri, Mastromatteo, Chillo, & Del Nobile, 2010; Ogawa, Kobayashi, & Adachi, 2011). We normalized therefore the cooking times with the initial surface area of the samples as proposed by Ogawa et al. (2011). Surface area strictly correlates with diameter$^2$, thus the presented unit for normalized cooking times is $[\text{time} \cdot \text{diameter}^{-2}]$.

Due to the limited amounts of available samples, weight and length increase were determined for two cooking times only. Other studies have shown that if there are differences in water absorption rate between samples, they are persistent throughout the cooking process (Cafieri et al., 2010; Ogawa & Adachi, 2013a). For both times measured, the starch-rich S40D60 seemed to absorb more water than the other samples (Fig. 2). The reference and the two gluten-rich pasta samples did not show any difference. The same behavior was observed for the length increase, with S40D60 increasing more than the three other samples. Thus, only the sample with the lowest protein content of...
8.3% deviated in water absorption rate, while the samples with a wide range of protein contents of 13.9% to 43.7% did not differ. The results match observations by Sozer and Kaya (2008) and Del Nobile, Baiano, Conte, and Mocci (2005). They found no influence of protein content on water absorption rate for samples with a protein content of 11.7% to 15.5%. This indicates that there might be a threshold value for the protein content above which the water absorption rate might be independent of the protein content.

The presence of salt in the water influenced neither the amount of absorbed water nor the length increase. This is in agreement with recent findings of Ogawa and Adachi (2013a) who report no influence at a similar NaCl concentration (0.5%). However, higher salt levels (5% has been reported) decrease the amount of absorbed water (Ogawa & Adachi, 2013a; Sozer & Kaya, 2008).

3.2. Real-time magnetic resonance imaging

The chosen MRI set-up allowed studying the cooking process of pasta with a temporal resolution of 45 s. \(I_0\) and \(T_2\) maps for a complete cooking series are shown as an example for D100 cooked in distilled and salted water (Fig. 3). The two slices (only middle slice shown) were consistent and showed a similar cooking progress. The outer contour of the pasta was visible in the first maps (~2.1 min), which confirmed the water ingress and the beginning of starch gelatinization due to the cooking process. The gray region in the middle, which decreased with increasing the cooking time, represent the ungelatinized core of the pasta, as shown by polarized light micrographs (Fig. 3c). At this point, we want to emphasize that throughout the cooking, the pasta increased significantly in radius and length (see 3.1). Because of the length increase, the MR parameter maps reflect different parts of the pasta depending on cooking time. \(I_0\) maps may be used as a proxy for the water concentration (Steglich et al., 2014) if the signal has relaxed back to the equilibrium during the repetition time, i.e. the signal is not \(T_1\)-weighted. To estimate the degree of \(T_1\)-weighting of the \(I_0\) maps, \(T_1\) was measured at the end of each cooking series (Fig. 4a). The estimated \(T_1\) maps varied between the samples and S40D60 had on average the largest \(T_1\) values. As a result, \(I_0\) (corrected for \(T_1\)) and \(I_0\) differed in particular for S40D60 implying \(T_1\)-weighting in contrast to gluten-rich pasta (Fig. 4b + c). The \(I_0\) maps indicate that S40D60 absorbed the most water, which agrees
with the water absorption results measured by weight increase. In general, all pasta samples showed more or less \( T_1 \)-weighted \( I_0 \) values close to the water interface where \( I_0 \) represent the largest values. The uncorrected, \( T_1 \)-weighted \( I_0 \) parameter maps, although not reflecting the true water concentration, allowed nevertheless comparing the temporal changes throughout the cooking with and without salt in a qualitative manner.

Fig. 5a+bs hows \( T_1 \)-weighted \( I_0 \) and \( T_2 \) maps for selected times for all pasta samples cooked in distilled or salted water. The cooking process proceeded in the same pace for all pasta samples independently on the presence of salt in the cooking water at the observed temporal and spatial resolution. \( I_0 \) values tend to decrease close to the ungelatinized core, which is true for all model pasta. The distribution of \( I_0 \) values is rather homogeneous throughout the cooked regions, in particular for the S40D60 and D100. For the gluten-rich samples G20D80 and G40D60, the distribution of \( I_0 \) values seemed to be more heterogeneous. This indicates that the polymerization of gluten in combination with water absorption occurs not as homogeneous in high protein pasta compared to pasta containing more starch.

The \( T_2 \) maps are characterized by larger \( T_2 \) values (yellow) close to the water–pasta interface and shorter \( T_2 \) (red) towards the ungelatinized core. The smaller \( T_2 \) values arose from low water content, which was also indicated by lower \( I_0 \) values. This trend was found for all model pasta. No obvious difference could be found comparing the MR maps (\( I_0 \) and \( T_2 \)) obtained from pasta cooked in distilled and in salted water. This is consistent with Kojima, Horigane, Yoshida, Nagata, and Nagasawa (2001) who reported no effect of a 0.69% NaCl solution on \( T_2 \) of cooked wheat gel samples (compared to cooking in distilled water).

Visualizing the values of the \( T_2 \) maps in histograms allowed for a semi-quantitative comparison of the pasta samples. We chose smoothed histograms that present probability density estimates (PDEs) to illustrate the differences (Fig. 5c) occurring during the cooking. PDEs of \( T_2 \) are presented for the same cooking times as the \( T_2 \) maps shown in Fig. 5b. For each cooking time, the PDEs did not vary much with salt concentration while differences were found between the pasta samples. A difference in the amount of gluten in G20D80 and G40D60 yielded an almost identical PDE characterized by a narrow distribution with the shortest \( T_2 \). PDEs for D100 were located on the gluten-rich PDEs or between gluten-rich and S40D60 PDEs. The width of the PDEs seemed to broaden with increasing starch content and the PDE of S40D60 absorbed larger amounts of water in contrast to gluten-rich pasta. Increasing \( T_2 \) values with decreasing protein content was also reported for various stages of cooking in noodles (Kojima et al., 2004).

### 3.3. Water absorption kinetics

The decreasing radius of the ungelatinized core over cooking time can be seen as a measure for water absorption kinetics. The estimated inner radius from \( T_1 \)-weighted \( I_0 \) maps represents the average of two slices as a function of cooking time (Fig. 5d). Deviations within the same sample were small until the inner radius had reached about 30% of the initial radius. At this point in time, the standard deviations increased as the uncooked core is represented only by few voxels resulting in a large relative error. Additionally, the samples showed a somewhat heterogeneous inner structure with some small, randomly distributed air inclusions. This complicated the evaluation (a representative air inclusion can be seen in the polarized light micrograph for

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**Fig. 4.** MR parameter maps representing a) \( T_1 \), b) \( T_1 \)-weighted initial signal intensity (\( T_1-w I_0 \)) as well as c) corrected initial signal intensity (\( I_{0C} \)). Spaghetti was cooked for 15 min in distilled or salted water.
5.2 min in Fig. 3). The inner radii determined by MRI agreed well with the radii determined by polarized light microscopy. Again, the uncertainty increased when the radius was below 30% of the initial value. Still, the general pattern of a linear decrease at an early cooking stage and accelerated decrease at a later cooking stage is consistent with data reported by Del Nobile, Buonocore, Panizza, and Gambacorta (2003). The data indicated that neither salted water (0.7% NaCl) nor the protein content of the samples influence the water ingress rate (Fig. 5d).
Others have seen little to no influence of protein content as well (Cubadda et al., 2007; Del Nobile et al., 2005; Kojima et al., 2004); at least as far as high temperature drying is concerned. Differences may apply at low-temperature drying (Cubadda et al., 2007; Resmini & Pagani, 1983). In addition to the temperature, the behavior of the water absorption might be influenced as well by other factors during drying such as drying time or relative humidity.

Although the water ingress rate was independent on the protein content, S40D60 absorbed more water in total. Hence, starch gelatinization defines the water ingress rate, whereas in gelatinized zones the local water content is influenced by the protein content. Ogawa and Adachi (2013b) also showed that starch gelatinization regulates the water ingress into the uncooked pasta regions.

### 3.4. Light Microscopy

All samples showed gradual changes in microstructure from the surface to the core of the spaghetti (Fig. 6). Furthermore, samples cooked in distilled water showed at 7.6 min a distinct outer zone of strongly swollen, partly disintegrated and fused starch granules. Some amylose leaching was visible (can be seen in the image as dark blue), being most pronounced in S40D60. The degree of starch granule swelling decreased towards the core; but to different extents. In S40D60 starch granules were visibly swollen in the whole cross-section in contrast to the other samples, which showed a more heterogeneous swelling pattern. While some starch granules did swell in the core zone almost to the same extent as S40D60, other granules appeared unswollen and embedded in the protein matrix. It seems as if higher gluten concentrations and thus denser gluten network partly hindered starch granule swelling, but not starch gelatinizing (as presented in Fig. 5d).

At 13.1 min, the aforementioned microstructural changes progressed towards the core. S40D60 and D100 showed partly an open structure at the surface due to disintegrated starch granules. G20D80 and G40D60, conversely, still showed a continuous protein matrix, although starch granules disintegrated as well. Again, a denser protein network might limit the swelling capabilities of starch. Alternatively, the median

![Fig. 6. Representative parts of spaghetti cross-sections cooked for 7:36 min and 13:06 min in a) distilled and b) salted water. The sections were stained with Light Green and Lugol’s iodine solution. Protein appeared green, starch blue/violet. Small unstained areas show fiber structures; large unstained areas show air inclusions entrapped in the matrix. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
distance between starch granules increases with increasing protein content, which makes it more unlikely that neighboring granules can swell to such an extent that they fuse.

The microstructure of samples cooked in salted water did not differ much from samples cooked in distilled water. However, the protein matrix seemed to be more intact in the region close to the core compared to samples cooked in distilled water. This might be explained by the protein stabilizing effect of NaCl due to increasing hydrophobic interactions between gluten units (Peressini, Sensidoni, Pollini, & Cindio, 2000; Sozer & Kaya, 2008).

The micrographs and T2 maps were in good agreement. T2 maps showed the highest T2 values in the surface zone and this zone increased with cooking time, which can be related to the zone of strongly swollen and partly disintegrated starch granules. S40D60 showed the largest T2 values and had an open structure at 13.1 min. This open structure at the surface could explain that S40D60 had the highest water concentration at the surface (Fig. 4c), which correlated with the large T2 values found in the core. Finally, the more homogenous granule swelling in S40D60 agreed with the narrower PDE distribution, while the broader PDE distribution of G20D80 and G40D60 might be due to their more heterogeneous swelling (Fig. 5c).

4. Conclusions

The presented real-time MRI approach facilitates a method to monitor the cooking process of pasta. Microscopy, although time-consuming and invasive, is complementary to MRI and enabled a detailed characterization of the microstructure on the micrometer to millimeter length scales.

Remarkably, the pace of the water ingress was neither dependent on the pasta composition nor the addition of salt (0.7% NaCl) in the cooking water although the micrographs revealed significant differences in the microstructure. Taken MR parameter maps and micrographs together, an increase in gluten content leads to a more heterogeneous water distribution and microstructure. The results suggest that above a certain protein content, the microstructure, water uptake and swelling as well as water distribution are similar. Thus, the gluten content affects the local water content in the cooked (gelatinized) zone but not the water ingress.

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