Original paper

Factors Affecting the Suitability of Boiled Pasta with Tomato Sauce for Eating

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Pasta samples boiled for different times and mixed with tomato sauce were physically and chemically evaluated to determine the factors affecting the suitability of boiled pasta with tomato sauce for eating. Physical properties of the pasta boiled for the shortest time changed greatly when sauce was added. The texture of the pasta boiled for the longest time was soft, because the core lacked a non-gelatinized region. In a force–strain curve, the change in the force after the breaking point of the pasta boiled for the shortest time was the largest after sauce addition. The $T_2$ values and chlorine distribution of pasta samples showed that the amount of penetration of the sauce ingredients to the core of the pasta boiled for the shortest time was less than that of the pasta boiled for the longest time. These results suggest that small changes in the physical properties after the sauce addition, sufficient penetration of the sauce ingredients to the core, and the presence of a non-gelatinized region at the core are critical factors affecting the suitability of boiled pasta with tomato sauce for eating.

Keywords: spaghetti, tomato sauce, magnetic resonance imaging, X-ray fluorescence, $T_2$ images, NaCl

Introduction

Pasta originated in Italy and is now very common in Japan. It was first introduced to Japan at the end of the Edo period (1850s). In the 1950s, major Japanese pasta makers imported Italian fully automatic pasta production systems and began to produce pasta commercially. Since the 1980s, Japanese pasta menus have become increasingly varied in response to heightened interest in Italian food. Both in Italy and Japan, pasta boiled to be “al dente” is said to be superior (Ikegami, 2003; Nakamachi et al., 2004; Serventi and Sabban, 2012). In al dente pasta, a moderate-sized non-gelatinized region remains at the core (Irie et al., 2004). Although there may be physical or chemical reasons why pasta cooked al dente is preferred both in Italy and in Japan, no such reasons have yet been identified.

Regarding the quality of uncooked pasta, the effects of the protein content of the raw materials (durum semolina) and the drying temperature on the firmness of the pasta have been reported (Matsuo et al., 1982; Stefanis and Sgrulletta, 1990; Malcolmson et al., 1993; Novaro et al., 1993). Regarding the quality of boiled pasta, some researchers have reported evaluations using magnetic resonance imaging (MRI). Irie et al. (2004) reported the relationship between the moisture distribution of various types of pasta products and their texture using MRI, and Horigane et al. (2006) evaluated the moisture distribution and diffusion in cooked dry or fresh pasta using nuclear magnetic resonance (NMR) imaging and a diffusion model. Horigane et al. (2009) also reported the effects of seasonings on the physical properties and $T_2$ map of cooked spaghetti using MRI. In addition, Sekiyama et al. (2012) reported the $T_2$ distribution of boiled dry spaghetti measured using MRI and its internal structure observed by fluorescence microscopy. Thus, MRI has been shown to be an effective method of evaluating the moisture distribution in boiled pasta. On the other

Abbreviations: Cl, chlorine; MRI, magnetic resonance imaging; NMR, nuclear magnetic resonance; XRF, X-ray fluorescence.

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hand, regarding pasta sauce quality, Landy et al. (2002) reported the sensory and chemical changes in tomato sauce during storage, and Mirondo et al. (2015) investigated how peel removal affects the flavor and viscosity of hot- and cold-break tomato juice and sauce.

Because pasta is usually eaten with sauce, the quality of pasta should be evaluated with sauce. In recent years, studies on mutual pairing of multiple foods have been advancing (Ahn et al., 2011). For example, Donadini et al. (2008) evaluated ideal everyday Italian food and beer pairings, and Donadini et al. (2012) reported the hedonic response to chocolate and beverage pairing. In addition, as an evaluation of the interactions of foods that have been directly mixed, Traynor et al. (2013) studied the sensory and chemical interactions of pairing certain foods (basmati rice, bacon, and extra virgin olive oil) with banana; however, this combination is not globally common. Regarding the combination of pasta with pasta sauce, Cremer (1983) reported the sensory quality of spaghetti with meat sauce after various holding treatments and heating in an institutional microwave and convection ovens, and Al-Obaidy et al. (1984) compared the sensory qualities of freshly prepared spaghetti with meat sauce before and after hot holding on a cafeteria counter. Furthermore, Ogawa et al. (2015) reported the sauce retention capacity of dried pasta. However, no existing reports have discussed the physical and chemical suitability of pasta with sauce for eating. Because customers have recently become more interested in their food purchases, the physical and chemical evaluation of the suitability of pasta with sauce for eating is necessary to develop high-quality pasta dishes.

Regarding pasta and sauce, pasta boiled for a long time with sauce had been intuitively considered to be suitable for eating before the 19th century (Serventi and Sabban, 2012), while pasta boiled for too short of time with sauce has been considered to be unsuitable for eating (Ikegami, 2003). In this study, the quality of boiled pasta mixed with tomato sauce was physically and chemically evaluated to assess the factors that determine the suitability of pasta with sauce for eating.

**Materials and Methods**

**Pasta samples** Dried pasta (spaghetti) samples made from durum semolina were supplied by Nisshin Foods Co. (Tokyo, Japan). The initial diameter of the dry pasta strands was 1.7 ± 0.3 mm. When boiling the pasta, samples were placed in at least 10 times their weight of boiling tap water without the addition of salt.

**Tomato sauce** An ordinary type of tomato sauce was prepared according to the recipe given in Table 2. First, garlic was sautéed with olive oil (Bosco, Nisshin Oillio Group, Tokyo, Japan) to 110°C. Then, diced tomato (La Bonta, Di Leo Nobile S.p.A., Salerno, Italy) homogeneously pulverized by a blender, tomato paste (Kagome Co., Nagoya, Japan), salt (The Salt Industry Center of Japan, Tokyo, Japan), and tap water were added, and the sauce was stewed to 85°C for 30 min. The viscosity of the tomato sauce was measured by a viscometer at 60°C and 100 rpm (TV-25, Toki Sangyo Co., Tokyo, Japan). The viscosity was found to be 320 mPa·s.

**Microscopic observation of pasta samples with sauce** Boiled pasta samples (20 g) were immersed in pasta sauce (300 g, 60°C) for 2 min and then removed, prior to observation of their surface appearance using a digital microscope (VHX-2000, Keyence Co., Osaka, Japan) at a magnification of 10×, and the diameters of n = 5 strands from each sample were measured.

**Measurement of weights of retained sauce, adhered sauce, and absorbed sauce** Boiled pasta samples (20 g) were immersed in pasta sauce (300 g, 60°C) for 3 min and then removed, before being weighed. The weight of the retained sauce was estimated from the difference between the weights of the pasta before and after immersing in sauce. Then, the sauce coating the surface of the pasta samples (adhered sauce) was removed by passing a strand of

<table>
<thead>
<tr>
<th>Table 1. Properties of boiled pasta samples</th>
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<tr>
<td>Boiling time (min)</td>
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<tr>
<td>Weight increase by boiling (%)</td>
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<tr>
<td>Moisture content (% W. B.)</td>
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Values are mean ± SD (n = 4).

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<th>Table 2. Recipe for tomato sauce</th>
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<td>Ingredient</td>
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<tr>
<td>Olive oil</td>
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<td>Garlic</td>
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<tr>
<td>Diced tomato</td>
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<tr>
<td>Tomato paste</td>
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<tr>
<td>Salt</td>
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<tr>
<td>Water</td>
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<td>Total</td>
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The pasta samples were boiled for three different boiling times; samples with short, medium, and long times of 6.5, 8.5, and 11 min were denoted samples A, B, and C, respectively. Pasta boiled for the same time as sample B is considered to be al dente in Japan. This state was sensorially checked and supported by MRI as described previously (Irie et al., 2004). The increases in the weights of samples A, B, and C after boiling were 215%, 230%, and 245%, respectively (Table 1). All three samples were within the range of edible firmness.

**Boiling pasta samples** Dried pasta (spaghetti) samples made from durum semolina were supplied by Nisshin Foods Co. (Tokyo, Japan). The initial diameter of the dry pasta strands was 1.7 ± 0.3 mm. When boiling the pasta, samples were placed in at least 10 times their weight of boiling tap water without the addition of salt.
pasta through the hole of a 200-µL pipette tip (BIOP200RF, BM Equipment Co., Tokyo, Japan), as shown in Fig. 1A, and the pasta was weighed. The end of the pipette tip was cut to a diameter of 0.02 mm greater than the pasta diameter. The weight, \(w_{\text{abs}}\), of the absorbed sauce was obtained as the difference between the weights, \(w_{\text{ret}}\) and \(w_{\text{adh}}\), of the retained and adhered sauce, respectively, as

\[ w_{\text{abs}} = w_{\text{ret}} - w_{\text{adh}}. \]

The weights of the retained, adhered, and absorbed sauce were obtained for \(n = 12\) strands of pasta from each sample. A schematic showing the definitions of the retained, adhered, and absorbed sauce is shown in Fig. 1B.

**NaCl concentration, pH, and moisture content of pasta containing absorbed sauce**  The NaCl concentration, pH, and moisture content of pasta samples were measured after the removal of adhered sauce from the surface of pasta strands according to the method described above. Each pasta strand was homogeneously pulverized with a two-fold weight of reverse osmosis water in a blender. The NaCl concentration and pH were measured using an electrode-type salt meter (TS-999i, Tokokagaku Co., Tokyo, Japan) and a pH meter (F51, HORIBA, Kyoto, Japan), respectively. The moisture content on a wet weight basis was determined for \(n = 4\) strands from each sample by measuring the weight loss of the pasta after oven-drying for 2 h at 135°C.

**Changes in the physical properties of pasta after sauce addition**  Each boiled pasta sample (20 g) was immersed in pasta sauce (300 g, 60°C) for 5 min and then removed. The physical properties of the pasta samples before and after sauce addition were measured using a universal testing machine (RE2-33005B, Yamaden Co., Tokyo, Japan) at room temperature (25°C). A single pasta strand was mounted in a wedge-shaped probe, and the position of the probe and the load level were measured in real time. The probe speed was set to 0.5 mm/s. The force–strain curve of each sample (short, medium, and long boiling times) was calculated by averaging the data from \(n = 5\) strands of pasta measured 5–10 min after sauce addition. The change in peak force after sauce addition to the pasta was read from (i) in Fig. 3A. Additionally, the change in the force after the breaking point (hereafter called the breakdown force) in the sample with the added sauce was read from (ii) in Fig. 3A.

**\(T_2\) distribution measured by MRI**  Boiled pasta samples (20 g) were immersed in pasta sauce (300 g, 60°C) for 2 min and then removed, before being applied for \(T_2\) distribution examination. \(^1\)H MRI was performed using a 7.1-T micro-imaging system (DRX300WB, Bruker, Karlsruhe, Germany) with a 15-mm birdcage radio frequency coil and ParaVision imaging software (ver. 3.0.2, Bruker). Cooked pasta strands were cut into 1-cm lengths, placed on an acrylic plate, and wrapped with polyethylene film. These strands were fixed in an NMR tube (outer diameter of 15 mm) and measured using the multi-slice multi-echo pulse program (in the Bruker library) at 21°C. The repetition time, echo time, number of echoes, field of view, matrix size, and slice thickness were 3 s, 4 ms, 32, 10 mm × 5 mm, 128 × 64, and 1 mm, respectively. Consequently, the voxel size was 78 µm × 78 µm × 1,000 µm, and the total scan time was 192 s. The \(T_2\) value in each voxel was calculated as \(M = M_0 \exp(-T_2/T_2)\), where \(M\) is the signal intensity at echo time zero and \(T_2\) is the spin–spin relaxation time. \(T_2\) images were calculated from the sequential images of 32 echoes.
Chlorine (Cl) distribution measured by X-ray fluorescence
Boiled pasta samples (20 g) were immersed in pasta sauce (300 g, 60°C) for 2 min and then removed, before being rapidly frozen. The frozen pasta samples were embedded using optimal cutting temperature (OCT) compound before being sliced to a thickness of 90 μm using a microtome (CM3050S II, Leica Microsystems, Eisfeld, Germany) and mounted on a glass slide. After freeze-drying, the Cl distribution in the pasta slices was measured by detecting the chlorine intensity, which was used as the NaCl index because of the higher sensitivity of X-ray fluorescence (XRF) to chlorine than sodium. The distribution of Cl in the slices was observed in a vacuum using an XRF microscope (XGT7200, HORIBA, Kyoto, Japan). The tube voltage, tube current, irradiation diameter, irradiation time, field of view, and matrix size were 15 kV, 1.00 mA, Ø100 μm, 500 s × 30 times, 3.584 mm², and 256 × 256, respectively.

Statistical analysis
The obtained results for each test were presented as mean values ± standard deviation. Results were considered statistically significant at \( p < 0.05 \). Statistical analysis was performed using JMP® 11.2.0 (SAS Institute Inc., Cary, NC). Data were analyzed by one-way ANOVA, followed by the Tukey–Kramer honest significant difference multiple comparison test.

Results and Discussion

In this study, pasta samples were boiled for three different boiling times (Table 1) and were combined with tomato sauce prior to quality evaluation. All three samples were within the range of edible firmness. The second sample (sample B) was boiled for close to the recommended time of the pasta maker and was moderately firm, i.e., al dente. The texture of this pasta and the taste of the sauce are experienced together during mastication. This pasta sample was defined as the most suitable or harmonious with the sauce and suitable for eating, because the texture of the pasta and the taste of the sauce were not experienced in combination during mastication. The third sample (sample C) was boiled for slightly longer than the recommended time, which resulted in a softer texture; the sample lacked a non-gelatinized core and was not al dente. We considered that this pasta showed good harmony with the pasta sauce in terms of taste, because the pasta texture and the taste of the sauce were experienced together during mastication, similar to the al dente sample.

Microscopic observation
First, the surface appearance and strand diameter of each pasta sample were observed and measured to evaluate the effect of boiling time on the surface state and shape of the pasta mixed with sauce. The results are given in Fig. 2. No significant differences in the surface appearance or diameter among the three samples were observed. Thus, we were unable to evaluate the suitability of boiled pasta with tomato sauce for eating in reference to the microscopic observation data.

Measurement of weights of retained, adhered, and absorbed sauce
Next, the effect of boiling time on the weights of the retained, adhered, and absorbed sauce was examined. Certainly, the adhered sauce contributed to the taste; however, the absorbed sauce was also expected to be a factor in the suitability of boiled pasta with tomato sauce for eating, because we experience the sauce taste spread within a suitable sample when it is consumed and masticated. As shown in Table 3, the weights of the adhered sauce for samples A and B (short and medium boiling times, respectively) were greater than that for sample C (long boiling time); however, there were no significant differences among the weights of the absorbed sauce for the three samples. This result indicates that pasta boiled for a shorter time retains more sauce on its surface, whereas the boiling time has little effect on the amount of sauce absorbed by the pasta. It is possible that pasta boiled for a shorter time retains more sauce on its surface because, prior to sauce addition, its surface has a lower moisture content than pasta boiled for a longer time. In all samples, the weight of the adhered sauce accounted for more than 80% of the weight of the retained sauce. However, there were no significant differences among the weights...
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Table 3. Weight of retained, adhered, and absorbed sauce in or to pasta samples

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<th>A</th>
<th>B</th>
<th>C</th>
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<tr>
<td>Retained sauce (g/strand)</td>
<td>0.88 ± 0.23&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.77 ± 0.22&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.62 ± 0.09&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Adhered sauce (g/strand)</td>
<td>0.78 ± 0.22&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.70 ± 0.21&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.53 ± 0.09&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Absorbed sauce (g/strand)</td>
<td>0.09 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.08 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.09 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
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Pasta samples were immersed in tomato sauce (60°C) for 3 min, before retained, adhered, and absorbed sauce were estimated as shown in Fig. 1. Values are mean ± SD (n = 12). Different superscript letters indicate significant differences at p < 0.05.

Table 4. NaCl concentration, pH, and moisture content of uncooked pasta, sauce, and each of the pasta samples with absorbed sauce.

<table>
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<th>Pasta</th>
<th>Sauce</th>
<th>Pasta with absorbed sauce</th>
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<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>NaCl concentration (%)</td>
<td>0.02 ± 0.00</td>
<td>1.89 ± 0.00</td>
<td>1.08 ± 0.07&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>pH</td>
<td>6.52 ± 0.05</td>
<td>4.13 ± 0.01</td>
<td>4.80 ± 0.11&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Moisture content (%, W. B.)</td>
<td>-</td>
<td>90.3 ± 0.1</td>
<td>59.0 ± 0.4&lt;sup&gt;a&lt;/sup&gt;</td>
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Pasta samples were immersed in tomato sauce (60°C) for 3 min, before pasta with absorbed sauce were prepared as shown in Fig. 1. Values are mean ± SD (n = 4). Different superscript letters indicate significant differences at p < 0.05.

of the absorbed sauce for the three samples, which was expected to be a factor in the suitability of boiled pasta with tomato sauce for eating. Therefore, measurement of the weights of retained, adhered, and absorbed sauce could be used to determine the suitability of boiled pasta with tomato sauce for eating.

**NaCl concentration, pH, and moisture content of pasta with absorbed sauce** As the NaCl concentration, pH, and moisture content were considered factors affecting the taste of pasta, the effects of boiling time on the NaCl concentration, pH, and moisture content of whole strands of pasta with absorbed sauce were evaluated. The results are shown in Table 4. There were no differences in the NaCl concentration and pH among the pasta samples with absorbed sauce. However, sample C had a higher moisture content than the other two samples, indicating that boiling pasta for a longer time before immersing it in sauce results in pasta with a higher moisture content. This is because sample C had a high moisture content just after being boiled (Table 1), and thus a high moisture content is likely not related to differences among samples in the interaction of the pasta with the sauce. We could not evaluate the suitability of boiled pasta with tomato sauce for eating from measurement of the NaCl concentration, pH, and moisture content of whole strands of pasta with absorbed sauce.

**Changes in physical properties of pasta after sauce addition** As the physical properties of the pasta samples seemed to be related to a suitable texture, changes in the physical properties of the pasta samples after sauce addition were then measured. Changes in the peak and breakdown forces after sauce addition were calculated from force-strain curves. The results are shown in Fig. 3 and Table 5. Before the addition of sauce, the force–strain curve of sample A had two peaks because of the firmness of the sample, similar to results reported by Irie et al. (2017) (Fig. 3A).

The peak force of sample A before sauce addition was the largest among the samples. After sauce addition, the peak force of sample C was lower than those of samples A and B (Fig. 3). The change in the peak force of sample A after sauce addition ((i) in Fig. 3A) was 0.41 N (Table 5). The change in the peak force of sample C after sauce addition (Fig. 3) was 0.69 N, the largest among the samples. After sauce addition, the peak force of sample A decreased significantly, while the peak force of sample C increased significantly. This change was significantly larger than those of samples B and C, which were boiled for longer than sample A. As reported by Irie et al. (2017), pasta strands boiled for a short time, such as sample A, contained a very large non-gelatinized region just after boiling, whereas the non-gelatinized region of sample B was smaller than that of sample A. Sample C lacked a non-gelatinized region in the core. The physical properties of the gelatinized region were found to be more stable with respect to the texture than those of the non-gelatinized region just after boiling. Therefore, the large change in the peak force of the pasta after sauce addition suggested that a large non-gelatinized region remained. Furthermore, the breakdown force of sample A after sauce addition ((ii) in Fig. 3A) was 0.69 N, the largest among the three samples (Table 5). This is likely attributable to the dry and crumbly texture of sample A. Irie et al. (2004) reported that a breakdown force of about 0.5 N was considered brittle and reflective of an unsuitable texture. The value in this study was higher than that reported by Irie et al. (2004). Generally, the basic theory of cooking pasta is to gelatinize starch granules by the boiling process in order to stabilize the texture fully. It is not preferable that the texture of pasta changes gradually after it is boiled. The texture of pasta boiled for a short time (sample A) changed greatly after boiling and after sauce addition. At first, the texture of the non-gelatinized region of this pasta sample felt firm and crumbly, and later felt brittle with the penetration of the moisture of the sauce to the region. Thus, the large change in the peak force after sauce addition and the large breakdown force of
the pasta with the added sauce are factors that correlate to the pasta having an unsuitable texture.

Analysis of $T_2$ distribution of pasta after sauce addition The internal $T_2$ state of pasta whose physical properties were changed with the addition of sauce was analyzed using MRI to evaluate the degree of penetration of the sauce ingredients. In unseasoned pasta or white salted noodles, the $T_2$ values are considered to reflect the mobility of the water molecule and have been correlated with the moisture content (Kojima et al., 2001; Irie et al., 2004; Horigane et al., 2006). However, the experimental samples in this study were mixed with sauce composed of various ingredients. Therefore, the $T_2$ values may not only reflect the moisture content.

Figure 4 shows the $T_2$ images of the pasta samples and their profiles along the center line before and after sauce addition. Before sauce addition, the $T_2$ values at the cores of samples A and B were lower than the detection limit. These results indicate the

| Table 5. Changes in peak force and break down force of samples by addition of tomato sauce |
|--------------------------------------|--------|--------|--------|
|                                      | A      | B      | C      |
| Change in peak force (N)             | 0.41 ± 0.13$^a$ | 0.17 ± 0.01$^b$ | 0.23 ± 0.02$^b$ |
| Breakdown force (N)                  | 0.69 ± 0.11$^a$ | 0.39 ± 0.08$^b$ | 0.40 ± 0.14$^b$ |

Changes in peak force and break down force of samples by addition of tomato sauce were, respectively, obtained from (i) and (ii) of the force–strain curves as shown in Fig. 2A. Values are mean ± SD ($n$ = 5). Different superscript letters indicate significant differences at $p < 0.05$. 

Fig. 3. Physical properties of sample A (boiled for 6.5 min; A), sample B (boiled for 8.5 min; B), and sample C (boiled for 11 min; C) before and after being immersed in sauce for 3 min. The quantities of labeled (i) and (ii) in (A) show the definitions of the change in the peak force and the breakdown force by the addition of tomato sauce, respectively.
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The surface $T_2$ values of all the samples after sauce addition were lower than those before the addition, although the sauce added to the pasta samples had a much greater moisture content (90.3% ± 0.1%, Table 4) than all of the pasta samples (Table 1). Horigane et al. (2009) reported that monosodium glutamate caused the decrease in the $T_2$ value of pasta. Tomato contains glutamic acid, and the tomato sauce used in this study included sodium. Similarly, some of the ingredients of the tomato sauce may have caused the decrease in $T_2$ values of the surface of pasta samples.

The $T_2$ value of sample A in the core of the pasta with added sauce remained lower than the detection limit, as observed before sauce addition. Thus, the penetration of the sauce ingredients and moisture to the core of sample A could not be confirmed. The $T_2$ value of the core of sample B after sauce addition was higher than that before, indicating that the sauce moisture penetrated to the core. As the temperature of the pasta sauce (60°C) was below the gelatinizing temperature of wheat starch, the core of sample B could not gelatinize despite the penetration of moisture from the sauce. Therefore, sample B remained *al dente* even after the addition of sauce. The $T_2$ value of the core of sample C after sauce addition was almost the same as that before. This was because the two factors that increase the $T_2$ value (moisture) and decrease it (sauce ingredients) were mixed with each other.

**Analysis of the Cl distribution of pasta after sauce addition**

Next, the penetration of NaCl into the pasta after sauce addition was evaluated by determining the Cl distribution in freeze-dried slices of individual strands using XRF. The results are shown in Fig. 5. The Cl signal at the surface of the sample A slice was high, but that at the core was very low. The Cl signal was high at both the core and surface of the sample B slice. Finally, the Cl signal at the core of the sample C slice was slightly lower than that at the surface, but it was relatively high throughout the slice. Thus, the Cl signals in the cores of the sample B and C slices were high.

Although there were no significant differences among the weights of the absorbed sauce for the three sample (as shown in Table 3), the results described above indicate that the sauce ingredients, such as NaCl, penetrated to the cores of samples B and C, which were boiled for a longer time than sample A, and that their cores contained more moisture before sauce addition. As the $T_2$ distribution data showed that the core of sample A had little moisture, both moisture and the other ingredients of sauce seemed to hardly penetrate to the core of sample A. In samples B and C, it was considered that both moisture and the other sauce ingredients penetrate to the core. Particularly, pasta boiled for a long time, like sample C, had a large amount of moisture in the core, so it was easy for the sauce ingredients to penetrate to the core after sauce addition. These results suggest that the flavor compounds of the

**Fig. 4.** $T_2$ images obtained by MRI (upper row) and the corresponding profiles (lower row) along the center lines of pasta samples obtained before and after being immersed in sauce for 2 min.
sauce can be sensorially recognized more easily when we eat and masticate pasta boiled for a longer time and mixed with tomato sauce than that boiled for a shorter time. These results suggest that the movement of salt with the moisture in the pasta causes changes in the taste and texture, and that sufficient penetration of sauce ingredients, such as NaCl, is a key factor affecting the suitability of boiled pasta with tomato sauce for eating.

**Conclusion**

In this study, the quality of pasta mixed with tomato sauce was physically and chemically evaluated. Pasta samples were boiled for three different boiling times: 6.5, 8.5, and 11 min, before being immersed in tomato sauce. As a boiling time of 8.5 min produced al dente pasta, we here defined this sample as the most suitable for eating. The boiling time did not affect pasta appearance, weight of the absorbed sauce, pH, or NaCl concentration. Although the boiling time affected the weight of retained sauce, specifically the adhered sauce, and the moisture content, these factors were not related to the suitability of boiled pasta with tomato sauce for eating. The physical properties of the pasta boiled for the shortest time changed greatly after sauce addition. The change in the peak force in the force–strain curve after sauce addition was the largest for the pasta sample boiled for the shortest time. Additionally, the breakdown force of the pasta boiled for the shortest time was large.

It is not preferable that the texture of pasta changes gradually after it is boiled. The texture of boiled pasta is not stable when the contained starch granules are not fully gelatinized by boiling. The results of $T_2$ and Cl distribution measurements suggested that the degree of penetration of the sauce ingredients to the core of the pasta boiled for the shortest time was less than that of the pasta boiled for the longest time. Although there were no significant differences among the weights of the absorbed sauce with boiled pasta samples, the degree of penetration of the sauce ingredients to the core of the pasta was different. The moisture and the other ingredients in the sauce might not move together in the pasta. So, more sauce ingredients such as NaCl might penetrate in the pasta boiled for long time (sample C), whose moisture content was high, than in the pasta boiled for short time (sample A), even though there were no significant differences in the weights of absorbed sauce among all samples. It seems that it is not the total quantity of absorbed sauce, but the distribution or homogeneity of the sauce ingredients that is a critical factor in the suitability of boiled pasta with tomato sauce for eating. If there were only adhered sauce, we would experience a less complex taste during mastication. On the other hand, we would suitably experience the combined taste of adhered sauce and penetrated sauce with the taste of pasta if the sauce ingredients penetrated to the core.

The following three factors were found to greatly affect the
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**References**


