1) *A short running head:*

Measurement of moisture profile in pasta

Full title:

Measurement of moisture profiles in pasta during rehydration based on image processing

2) *Name of authors:*

Takenobu Ogawa · Shuji Adachi

3) *Institution with full addresses for each author:*

T. Ogawa · S. Adachi
Division of Food Science and Biotechnology, Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan

4) *Name, address, telephone and fax numbers, and e-mail address of author responsible for correspondence:*

S. Adachi
Sakyo-ku, Kyoto 606-8502, Japan
Tel.: +81-75-753-6286
Fax: +81-75-753-6285
E-mail address: adachi@kais.kyoto-u.ac.jp

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Abstract A method using an image processing technique was developed to measure the moisture profile in pasta during its rehydration process. The method is based on the increase in sample color brightness with increasing moisture content. Compared to currently used methods, this method has the advantage that moisture contents around 0.1 kg-H_2O/kg-d.m. can be easily measured at a spatial resolution of 1.6 μm. The moisture profiles obtained by this method suggested that penetration of water into small holes and cracks on the pasta surface, water diffusion in the pasta, and structural relaxation of the protein matrix play important roles in the rehydration mechanism. It was also suggested that starch granule gelatinization prevented water migration into the interior portion of the pasta.

Keywords Digital camera · Image processing technique · Moisture profile · Pasta · Rehydration

Introduction

Drying is an effective method for extending the shell-life of food during storage. The primary objective of food drying is to decrease the moisture content of the food to a level at which microbial spoilage is minimized. Dried products are usually rehydrated prior to their use or consumption. While the rehydration process aims to restore the properties of the raw materials, it can affect food quality. Therefore, the rehydration process governs the quality and properties of the food materials to be consumed; thus, it is important to fully understand the phenomena occurring during the rehydration of dried food.

Many papers have focused on the rehydration of dried food, such as apple (Atarés et al. 2009), orange (Diaz, et al. 2003), date palm fruit (Falade et al. 2007), shiitake mushrooms (García-Segovia et al. 2011), candied mango (Giraldo et al. 2006), mango (Maldonado et al. 2010), carrot (Nayak et al. 2006; Saguy et al. 2005a), and water chestnut (Singh et al. 2008). The rehydration process is typically analyzed based on Fick’s 2nd law of diffusion. The process of air-dried *Morchella esculenta* mushrooms (García-Pascual et al. 2006), broccoli stem (Sanjuán et al. 1999), and chikpeas (Yildirim et al. 2011) was investigated and could be well expressed by the law at different temperatures. Moreover, the rehydration process of fresh penne pasta at 20-80 °C was reported to be characterized by two effective diffusion coefficients using the law (Cunningham et al. 2007). However, a recent study showed that the actual process of moisture migration is not diffusion-controlled, proposing instead several other mechanisms, such as water imbibition, capillarity and flow in porous media (Lee et al. 2006; Saguy et al. 2005b). Although many models have been proposed to describe water migration in dried food during rehydration, the key mechanism controlling migration remains unclear.

The average moisture content of an entire sample is usually measured in order to validate a proposed model, although the moisture profile is numerically solved (Temmerman et al. 2007). One reason for taking such a measurement is the absence of an adequate method to obtain a precise moisture profile of the sample and to verify the numerical results. The absence of an adequate method makes it difficult to discern or interpret the mechanism controlling water migration during rehydration. Rehydration curves, which express changes in the average moisture content over time and are obtained by numerically solving the various models based on Fick’s 2nd law of diffusion, are of the hyperbolic type and satisfactorily fit the experimental data (Cunningham et al. 2007; Del Nobile et al. 2003; García-Pascual et al. 2006; Sanjuán et al. 1999; Yildirim et al. 2011). However, such results are insufficient to judge the appropriateness of the models, and the actual measurement of a precise moisture profile is unavailable for verification.

Nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) are powerful techniques to measure the moisture profile of foods. The moisture profiles of rice grains during cooking (Horigane et al. 2006), noodles during dehydration or rehydration (Sekiyama et al. 2012; Hills et al. 1996; Hills et al. 1997; Irie et al. 2004), and cheese during brining (Altan et al. 2011) were measured using these techniques. Although these techniques can provide information regarding moisture profiles, the accuracy of the measurement is insufficient to verify the numerically calculated profile due to the following four limitations: The minimum moisture content measureable by the techniques is high. For example, a moisture content less than 0.67 kg-H_2O/kg-d.m. cannot be measured for pasta due to fast water proton relaxation (Irie et al. 2004), although the pasta is rehydrated from a moisture content of approximately 0.11 kg-H_2O/kg-d.m. Another limitation is low spatial resolution. During MRI measurement, the moisture content is evaluated every 65 μm at best (Horigane et al. 2006). That is, only about 12 points of data can be obtained for pasta having a radius of 0.8 mm. Additionally, the measurement is time-consuming. The MRI technique takes a few minutes to obtain a moisture profile of a sample; however, the moisture profile of a sample, such as pasta, changes within a few minutes. Finally, the cost of equipment, such as NMR and MRI, is high. Therefore, the development of a method without these limitations would aid in elucidating the mechanism controlling water migration in dried foods.

Dried pasta is yellowish or yellowish brown, and becomes lighter as the moisture content increases. We focused on the color change of pasta during rehydration in developing a new method, using a digital camera, to precisely measure the moisture content (0.1 kg-H_2O/kg-d.m. or higher) of pasta. Notably, the sample must be cut in order to measure the cross-sectional moisture profile. A digital camera can acquire the color distribution of a sample, and currently available cameras have high pixels, which provides high-resolution images. The moisture profile measured by our method would enable us to elucidate phenomena in the rehydration process. Moreover, development of this method is the first step in understanding the mechanism controlling water migration during food rehydration.

Materials and methods

Materials

Two kinds of dried pasta were used. One was cylindrical pasta (spaghettini) supplied by Nisshin Foods, Inc. (Tokyo, Japan) and another was slab pasta (lasagna; De Cecco, Fara San Martino, Italy) purchased from a local supermarket.

The spaghettini was made from durum semolina. The sample was prepared under the following conditions: the drying temperature was increased from 50 ºC to 85 ºC during the first 60 min, maintained at 85 ºC for 300 min and decreased to 30 ºC during the last 30 min. After the drying process the cylindrical sample had an initial diameter of 1.60 mm and an initial moisture content of 0.11 kg-H_2O/kg-d.m. The carbohydrate, protein and fat contents were 72, 13 and 2 % (w/w), respectively.

The lasagna was also made from durum semolina. The sample had an initial thickness of 1.04 mm and an initial moisture content of 0.10 kg-H_2O/kg-d.m.

Rehydration of pasta

Culture tubes containing approximately 50 mL of distilled water were equilibrated at 100 °C in a temperature-controlled water bath (Thermominder SD; Taitec, Saitama, Japan). The spaghettini and lasagna were cut into 9-cm-lengths, of approximately 0.27 g, and 6.5-cm-lengths × 2-cm-depths, of approximately 1.90 g, respectively, and rehydrated by immersion in the culture tube. The sample was removed from the tube at the specified time, as shown later, and immediately carefully blotted with Kimtowels and Kimwipes (Nippon Paper Crecia, Tokyo, Japan) to remove excess water. One sample was used for each rehydration time.

Apparent density

After rehydration, the sample was wrapped in polyethylene sealing film to prevent moisture loss, and then placed in the temperature-controlled oven at 70 °C for 3 days in order to equalize the moisture distribution in the sample. Next, sample volume, V, was measured by a displacement technique using a pycnometer (25 mL; Sogorikagaku Glass Works, Kyoto, Japan) containing dodecane (density = 749 kg/m^3), with the assumption that dodecane penetration into the sample can be ignored. The apparent density of the rehydrated pasta, ρ, was calculated using Eq. (1).

$$\rho = w_0 / V \tag{1}$$

where w_0 is the sample weight after 3 days at 70 °C, measured by an AUW320 electronic balance (Shimadzu, Kyoto, Japan) prior to volume measurement. Each experiment was performed in duplicate.

Proposed method

As mentioned above, the method proposed in this study is based on the increase in sample color brightness with increasing moisture content. To obtain the moisture profile, a cross-sectional image of the sample is taken. The method consists of the five following steps:

The first step is the preparation of two sets of rehydrated pasta samples; one is used to measure the moisture profile and the other is used for making a calibration curve. The samples used for measuring the moisture profile and for making a calibration curve were rehydrated for 1, 10.2, 14.7 and 20 min and for 1, 3, 6, 9, 12, 15, 21, 25 and 30 min, respectively, under the same conditions. Then, only the samples for making a calibration curve were wrapped in polyethylene sealing film to prevent moisture loss, and placed in a temperature-controlled oven at 70 °C for 3 days to equalize the moisture distribution in the samples. Both sets of samples were subjected to steps two and three.

In step two, cross-sectional images were taken using a digital camera (Fig. 1). The rehydrated sample was cut crosswise using a sharp stainless-steel blade and covered with a light shield, the diameter or the thickness of which was the same as that of the sample. Both the light shield and the inner surface of an illumination box had an emissivity of 0.94. The cross-section of the laterally shielded sample was illuminated by two cold light illuminators (PICL-NSX; NPI, Tokyo, Japan) from both sides of the sample and photographed using a high-resolution digital camera (EOS-40D; Canon, Tokyo, Japan) with a 65-mm lens (MP-E 65 mm; Canon) in JPEG format. One image was taken for each sample. The image had 3888 × 2592 pixels, indicating that the spatial resolution of the proposed method was about 1.6 µm per pixel, which was about 40 times higher in the spatial resolution than those of MRI methods (Sekiyama et al. 2012; Horigane et al. 2006; Irie et al. 2004). Then, the area without the cross-section of sample in the image was manually eliminated using Photoshop CS4 extended (Adobe Systems Inc., San Jose, US-CA, USA).

The third step involved digital image processing using two software packages: Mathematica 7 (Wolfram Research, Champaign, IL, USA) and Origin 8.1J (OriginLab, Northampton, MA, USA). The original 24-bit RGB color image, obtained in step 2, was pixelated into red, green and blue images. Although the red, green and blue images had the same quality and could be equally used in principle, the blue image was used in this paper as an example. The image was converted into an 8-bit gray-scale format using Origin 8.1J. In order to visually clarify the gray level of the image, the original gray-level G_0 of each pixel was converted to the level G_γ through a gamma correction (Takagi et al. 2004) using Eq. (2), and G_γ was further converted to the level G_c through a contrast correction (Takagi et al. 2004) using Eq. (3).

$$G_\gamma = 255(G_0 / 255)^{0.5} \tag{2}$$

$$G_c = 2 \times G_\gamma - 255/2 \tag{3}$$

In step 4, the calibration curve was prepared, which correlates the corrected gray level G_c with the moisture content X, determined by drying each sample at 135 °C for 5 h in a convection drying oven (DO-300FA; As One, Osaka, Japan) immediately after the image acquisition in step 2. Moisture content was determined using the following equation.

$$X = (w_0 - w_1)/w_1 \tag{4}$$

where w_0 and w_1 are the sample weights before and after drying, respectively.

In the final step, the corrected gray level G_c of each pixel in the sample image was converted to the moisture content using the calibration curve, in order to obtain the moisture profile of the rehydrated pasta.

The measurements were conducted in at least duplicate for every sample rehydrated for different times. The reliability of the moisture profiles was examined as shown in the following section. The accuracy of the calibration curves was expressed by standard deviation for each point.

Verification of accuracy

The rood mean square error (RMSE) (Eq. (5)) was used to evaluate the accuracy of the proposed method.

$$\mathrm{RMSE} = \sqrt{\frac{\sum(\overline{X}_{\mathrm{cal}} - \overline{X}_{\mathrm{obs}})^2}{N}} \tag{5}$$

where $\overline{X}_{\mathrm{cal}}$ and $\overline{X}_{\mathrm{obs}}$ are the average moisture content of a sample calculated by Eq. (6) from the moisture profile and the experimentally observed one (Eq. (4)), respectively, and N is the number of experimental values.

$$\overline{X}_{\mathrm{cal}} = \int_V \frac{\rho(X)\cdot X}{X+1}\,dV \Big/ \int_V \frac{\rho(X)}{X+1}\,dV \tag{6}$$

where $\rho(X)$ is the apparent density at the moisture content X. The dependence of X on $\rho(X)$ is empirically represented by Eq. (7).

$$\rho(X) = A + B\exp(CX) \tag{7}$$

where A, B and C are constants.

Results and discussion

Gray level profile

Figure 2 shows images of the cross-sections of spaghettini and lasagna rehydrated for 10.2 min and 14.7 min, respectively, at which points the pastas were optimally cooked to the state termed *al dente*. Images (a) and (b) in Fig. 2 are the original and processed ones, respectively. The color of the circumferential (A) and rectangular (B) regions in which the water penetrated was brightened and whitened in images (a) and (b) in Fig. 2, respectively.

A gray-level profiles in the radial direction (A-b) and the thickness one (B-b) of the cross-sectional images of Fig. 2 were converted to the moisture profiles using the calibration curves (see below) and is represented by the thin line in Fig. 3 (shown only for spaghettini). The inset in Fig. 3 is the extended profile in the x-axis range of 0.325 to 0.365. Although the thin line appears to have a jagged pattern, there are obviously convex or concave patterns, as shown by the circles in the extended profile. Each circle corresponds to a pixel. Therefore, the jagged thin line was not ascribed to measurement noise, but to the high spatial resolution of the proposed method.

Starch gelatinization does not occur uniformly (Nagao et al. 2006). Large starch granules usually gelatinize faster, and gelatinization begins in an amorphous region of the starch granule. The pitch of the convex or concave pattern was about 20 µm, which was in the same order as the 2- to 40-µm size of a starch granule (Nagao et al. 2006). Therefore, the jagged patterns expressed by the thin line in Fig. 3 can be ascribed to the nonuniformity of the starch gelatinization. The spatial resolution of 1.6 μm in the proposed method allows for the estimation of nonhomogeneous rehydration behavior in pasta.

Calibration curve

The insets in Fig. 4 show cross-sectional images of the spaghettini with different, but homogeneous moisture contents. As the moisture content increased, the color of the image changed from black to white. The calibration curve, which correlates the gray level G_c ($0 \leq G_c \leq 255$) to the moisture content X, is shown in Fig. 4, and can be expressed by the quadratic function Eq. (8).

$$X = aG_c^{\,2} + bG_c + c \tag{8}$$

where a, b and c are constants. The G_c values were obtained by averaging the gay levels of all pixels in the cross-sectional image. The gray levels of 0 and 255 represent black and white, respectively. The constants a, b and c were determined to best-fit the observed moisture contents to the calculated ones using the Solver of Microsoft Office Excel® 2010, and were 4.54×10^{-5}, 4.03×10^{-3} and -3.06×10^{-1} for spaghettini, respectively, and 4.24×10^{-5}, 2.69×10^{-3} and -6.17×10^{-2} for lasagna, respectively. The correlation coefficient (R^2) was 0.978 at minimum, indicating the accuracy of Eq. (8) and the validity of the proposed method.

Moisture contents lower than 0.67 kg-H_2O/kg-d.m. cannot be measured by the currently used MRI method due to fast water proton relaxation (Irie et al. 2004). The calibration curve showed a clear one-to-one relationship in the moisture content range of 0.10 to 2.85 kg-H_2O/kg-d.m. Therefore, the proposed method can satisfactorily obtain moisture profiles for samples with low moisture content.

Moisture profile

The thick line in Fig. 3 shows the gray-level profile, which was obtained by dividing the image into ten segments shown by broken lines in Fig. 2 A-b and B-b and by averaging the gray levels at the same distance from the center of the segments. The profile expressed by the thin line indicates, in detail, the rehydration behavior. On the other hand, the thick line shows the averaged moisture profile in the sample. Figures 5 A and B show the averaged moisture profiles of spaghettini rehydrated for 0, 1, 10.2 and 20 min and lasagna rehydrated for 0, 1, 14.7 and 20 min, respectively. The profile at 0 min represents the dried pasta. The moisture profile in the *al dente* pasta, which was rehydrated for 10.2 min and 14.7 min for spaghettini and lasagna, respectively, was measured by the proposed method for the first time, as our method was able to measure a lower moisture content than the currently used method.

The spaghettini and lasagna have different characteristics, such as compositions, shape, drying condition, microstructure, initial moisture content and degree of gelatinization. However, the moisture profiles during their rehydration were similar in shape. This fact indicates that the phenomena controlling water migration during rehydration are the same even if some characteristics of pasta are different.

During the first 1 min, swelling occurred in an approx. 0.2-mm region near the surface, and the moisture content remained at the same level as that of the dried pasta in the inner region. The profiles at 0 and 1 min indicated that water quickly penetrated only near the surface. Based on SEM measurements, many small holes and cracks were reported on the surface of the pasta (Cunina et al. 1995; Dexter et al. 1978). Water entered the pasta through these small surface holes and cracks. The fact that the region near the surface had a flat moisture profile, and that there was no gradient in the profile, suggested that water imbibition during the early stage was not attributable to water diffusion, but water filling of the holes and cracks.

The extent of gelatinization was assessed by observing the birefringence in the starch/water system during heat treatment, revealing that gelatinization was complete within 1 min (Watanabe 2004). This indicated that starch gelatinization is a fast process. However, the moisture content on the surface gradually increased with time (Fig. 5). Our previous study (Ogawa et al. 2013; Ogawa et al. 2011) showed that the average moisture content of pasta increased up to about 9 kg-H_2O/kg-d.m. This indicated that the gelatinization of starch granules in the sample, even with 20 min-rehydration, did not reach equilibrium, and that swelling of the granules was restricted. In previous studies, while dried pasta showed a homogeneous internal structure, such that the starch granules were deeply embedded in a protein matrix, the structure below the surface appeared to be a honeycomb-like structure after a 4-min rehydration (Cunina et al. 1995; Dexter et al. 1978). The protein matrix, which had shrunk during drying, appeared to relax in structure during rehydration, and the starch granules gradually swelled due to gelatinization. Therefore, the structural relaxation process of the protein matrix appears to play an important role in alterations in the moisture content of samples during rehydration.

The moisture profiles observed for the samples rehydrated for 10.2 or 14.7 and 20 min showed two features. One was the flat moisture profile near the surface, and the other was the parabolic distribution of the moisture content in the inner region. The latter feature suggested that the water migration in the region was diffusion-controlled, while the former feature suggested that the diffusion of water was not the rate-limiting step for rehydration near the surface. As mentioned above, the moisture content near the surface of the sample rehydrated for 20 min was much lower than the equilibrium content, and the starch granules in the sample had the potential to absorb more water. Therefore, most of the water supplied from the bulk phase would be sorbed by the starch granules that increased the moisture content near the surface. In the inner region, diffusion of water occurred according to the gradient in the moisture content, and the profile gradually shifted to the higher level. However, the consumption of water by starch granule sorption near the surface restricted the penetration of water into the inner region. The water sorption near the surface expanded the region with the flat moisture profile, as can be seen from the profiles at 10.2 or 14.7 and 20 min.

Accuracy of measurement

The constants *A*, *B* and *C* in Eq. (7) were 1.12, 0.415 and -0.785 for the spaghettini, respectively, and 1.08, 0.500 and -1.455 for the lasagna, respectively. The correlation coefficient (R^2) was 0.985 at minimum, indicating the accuracy of Eq. (7) as shown in Fig. 6. The $\overline{X}_{\mathrm{cal}}$ and $\overline{X}_{\mathrm{obs}}$ values for the spaghettini rehydrated for 0, 1, 10.2 and 20 min and for the lasagna rehydrated for 0, 1, 14.7 and 20 min are plotted in Fig. 7. The RMSE was 0.149 and 0.175 for spaghettini and lasagna, respectively, indicating the high accuracy of the proposed method for moisture content determinations in pasta.

Conclusions

When pasta is rehydrated, its color brightness is altered. Based on this fact, a method was developed to measure the moisture profile in pasta using a digital camera and an image processing technique. The method allowed for the precise quantification of a moisture content of 0.1 kg-H_2O/kg-d.m., with a spatial resolution of 1.6 µm. The high-resolution profile revealed that starch granules were non-uniformly gelatinized during rehydration. The average moisture content, calculated from the moisture profile, was well correlated with that experimentally observed. The good correlation demonstrated the accuracy of the proposed method. The changes in the profile over time suggested that small holes and cracks near the pasta surface were quickly filled with water, and that the region near the surface gradually expanded due to structural relaxation of the protein matrix. It was also suggested that water migration occurred via diffusion in the inner region, and that gelatinization of the starch granules restricted the water diffusion. Moreover, it was shown that the phenomena controlling water migration during rehydration are common for spaghettini and lasagna, which are different in some characteristics.

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References

Altan, A., Oztop, M.H., McCarthy, K.L., & McCarthy, M.J. (2011). Monitoring changes in feta cheese during brining by magnetic resonance imaging and NMR relaxometry. *Journal of Food Engineering*, *107*(2), 200-207.

Atarés, L., Chiralt, A., & González-Martínez, C. (2009). Effect of the impregnated solute on air drying and rehydration of apple slices (cv. Granny Smith). *Journal of Food Engineering*, *91*(2), 305-310.

Cunina, C., Handschina, S., Waltherb, P., & Eschera, F. (1995). Structural changes of starch during cooking of durum wheat pasta. *LWT-Food Science and Technology*, *28*(3), 323-328.

Cunningham, S.E., McMinn, W.A.M., Magee, T.R.A., & Richardson, P.S. (2007). Modelling water absorption of pasta during soaking. *Journal of Food Engineering*, *82*(4), 600-607.

Del Nobile, M.A., Buonocore, G.G., Panizza, A., & Gambacorta, G. (2003). Modeling the spaghetti hydration kinetics during cooking and overcooking. *Journal of Food Science*, *68*(4), 1316-1323.

Dexter, J.E., Dronzek, B.L., & Matsuo, R.R. (1978). Scanning Electron Microscopy of Cooked Spaghetti. *Cereal Chemistry*, *55*(1), 23-30.

Díaz, G.R., Martínez-Monzó, J., Fito, P., & Chiralt, A. (2003). Modelling of dehydration-rehydration of orange slices in combined microwave/air drying. *Innovative Food Science & Emerging Technologies*, *4*(2), 203-209.

Falade, K.O., & Abbo, E.S. (2007). Air-drying and rehydration characteristics of date palm (*Phoenix dactylifera L.*) fruits. *Journal of Food Engineering*, *79*(2), 724-730.

García-Pascual, P., Sanjuán, N., Melis, R., & Mulet, A. (2006). *Morchella esculenta* (morel) rehydration process modeling. *Journal of Food Engineering*, *72*(4), 346-353.

García-Segovia, P., Andrés-Bello, A., & Martínez-Monzó, J. (2011). Rehydration of air-dried Shiitake mushroom (*Lentinus edodes*) caps: Comparison of conventional and vacuum water immersion processes. *LWT - Food Science and Technology*, *44*(2), 480-488.

Giraldo, G., Vázquez, R., Martín-Esparza, M.E., & Chiralt, A. (2006). Rehydration kinetics and soluble solids lixiviation of candied mango fruit as affected by sucrose concentration. *Journal of Food Engineering*, *77*(4), 825-834.

Hills, B.P., Babonneau, F., Quantin, V.M., Gaudet, F., & Belton, P.S. (1996). Radial NMR microimaging studies of the rehydration of extruded pasta. *Journal of Food Engineering*, *27*(1), 71-86.

Hills, B.P., Godward, J., & Wright, K.M. (1997). Fast radial NMR microimaging studies of pasta drying. *Journal of Food Engineering*, *33*(3/4), 321-335.

Horigane, A.K., Takahashi, H., Maruyama, S., Ohtsubo, K., & Yoshida, M. (2006). Water penetration into rice grains during soaking observed by gradient echo magnetic resonance imaging. *Journal of Cereal Science*, *44*(3), 307-316.

Irie, K., Horigane, A.K., Naito, S., Motoi, H., & Yoshida, M. (2004). Moisture distribution and texture of various types of cooked spaghetti. *Cereal Chemistry*, *81*(3), 350-355.

Lee, K.T., Farid, M., & Nguang, S.K. (2006). The mathematical modelling of the rehydration characteristics of fruits. *Journal of Food Engineering*, *72*(1), 16-23.

Maldonado, S., Arnau, E., & Bertuzzi, M.A. (2010). Effect of temperature and pretreatment on water diffusion during rehydration of dehydrated mangoes. *Journal of Food Engineering*, *96*(3), 333-341.

Nagao, S., Seko, H., Endo, S.,Uchida, M., Imai, T., Seguchi, M., & Shimada, J. (2006). Wheat Science (in Japanese; Komugi no Kagaku) (6th ed., p. 88). Asakura Shoten, Tokyo, Japan.

Nayak, C.A., Suguna, K., & Rastogi, N.K. (2006). Combined effect of gamma-irradiation and osmotic treatment on mass transfer during rehydration of carrots. *Journal of Food Engineering*, *74*(1), 134-142.

Ogawa, T., & Adachi, S. (2013). Effect of salts on water sorption kinetics of dried pasta. *Bioscience, Biotechnology, and Biochemistry*, *77*(2), 249-252.

Ogawa, T., Kobayashi, T., & Adachi, S. (2011). Water sorption kinetics of spaghetti at different temperatures. *Food and Bioproducts Processing*, *89*(2), 135-141.

Saguy, I.S., Marabi, A., & Wallach, R. (2005a). Liquid imbibition during rehydration of dry porous foods. *Innovative Food Science & Emerging Technologies*, *6*(1), 37-43.

Saguy, I.S., Marabi, A., & Wallach, R. (2005b). New approach to model rehydration of dry food particulates utilizing principles of liquid transport in porous media. *Trends in Food Science & Technology*, *16*(11), 495-506.

Sanjuán, N., Simal, S., Bon, J., & Mulet, A. (1999). Modelling of broccoli stems rehydration process. *Journal of Food Engineering*, *42*(1), 27-31.

Sekiyama, Y., Horigane, A.K., Ono, H., Irie, K., Maeda, T., & Yoshida, M. (2012). T2 distribution of boiled dry spaghetti measured by MRI and its internal structure observed by fluorescence microscopy. *Food Research International*, *48*(2), 374-379.

Singh, G.D., Sharma, R., Bawa, A.S., & Saxena, D.C. (2008). Drying and rehydration characteristics of water chestnut (*Trapa natans*) as a function of drying air temperature. *Journal of Food Engineering*, *87*(2), 213-221.

Takagi M. & Shimoda H. (ed) (2004). Handbook of image analysis (revised edition). University of Tokyo Press, Tokyo, Japan.

Temmerman, J.D., Verboven, P., Nicolaı¨, B., & Ramon, H. (2007). Modelling of transient moisture concentration of semolina pasta during air drying. *Journal of Food Engineering*, *80*(3), 892-903.

Watanabe, H. (2004). The factor which governs water migration in starchy foods. *Japan Journal of Food Engineering*, *5*(3), 143-151.

Yildirim, A., Öner, M.D., & Bayram, M. (2011). Fitting Fick's model to analyze water diffusion into chickpeas during soaking with ultrasound treatment. *Journal of Food Engineering*, *104*(1), 134-142.

Legends

Fig. 1. Equipment used in the proposed method.

Fig. 2. Cross-sectional images of the spaghettini rehydrated for 10.2 min (A-a and -b) and the lasagna rehydrated for 14.7 min (B-a and -b). (a) Original image and (b) digitally processed image. Broken lines show the segments of moisture profiles as an example.

Fig. 3. Gray-level profile of the cross-sectional image of spaghettini rehydrated for 10.2 min. Inset: The extended profile.

Fig. 4. Relationships between the moisture content and gray level in spaghettini (—○—) and lasagna (- -●- -) with homogeneous moisture distribution. Bars indicate standard deviation. The pictures in the figure are the digitally processed cross-sectional images obtained from spaghettini with homogenous moisture contents of 1.12 ± 0.02 and 2.89 ± 0.12 kg-H_2O/kg-d.m., indicated by arrows.

Fig. 5. Moisture profiles of spaghettini (A) rehydrated for 0, 1, 10.2 and 20 min and lasagna (B) rehydrated for 0, 1, 14.7 and 20 min, respectively.

Fig. 6. Dependence of apparent density on average moisture content in spaghettini (—○—) and lasagna (- -●- -). Bars indicate standard deviation.

Fig. 7. Correlation between the experimentally observed average moisture content, $\overline{X}_{\mathrm{obs}}$, and the moisture content calculated from the moisture profile, $\overline{X}_{\mathrm{cal}}$, in spaghettini rehydrated for (△) 0 min, (○) 1 min, (◇) 10.2 min and (□) 20 min and lasagna rehydrated for (▲) 0 min, (●) 1 min, (▼) 14.7 min and (■) 20 min. Bars indicating the standard deviation are behind the symbols.

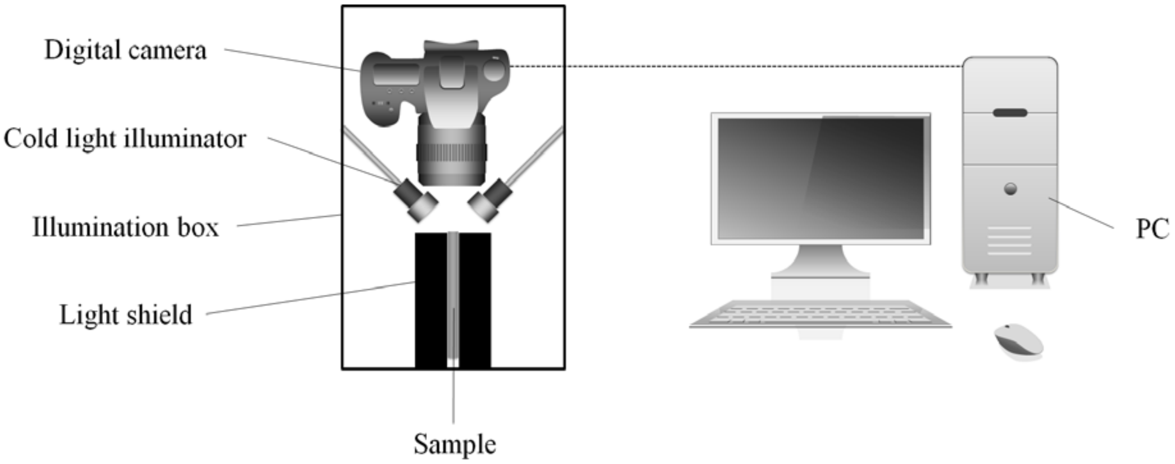

Fig. 1.

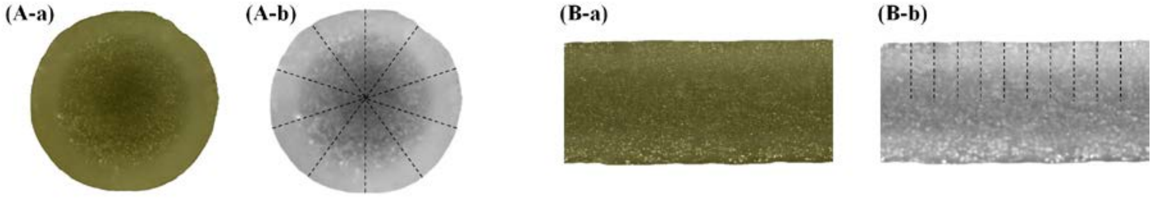

Fig. 2.

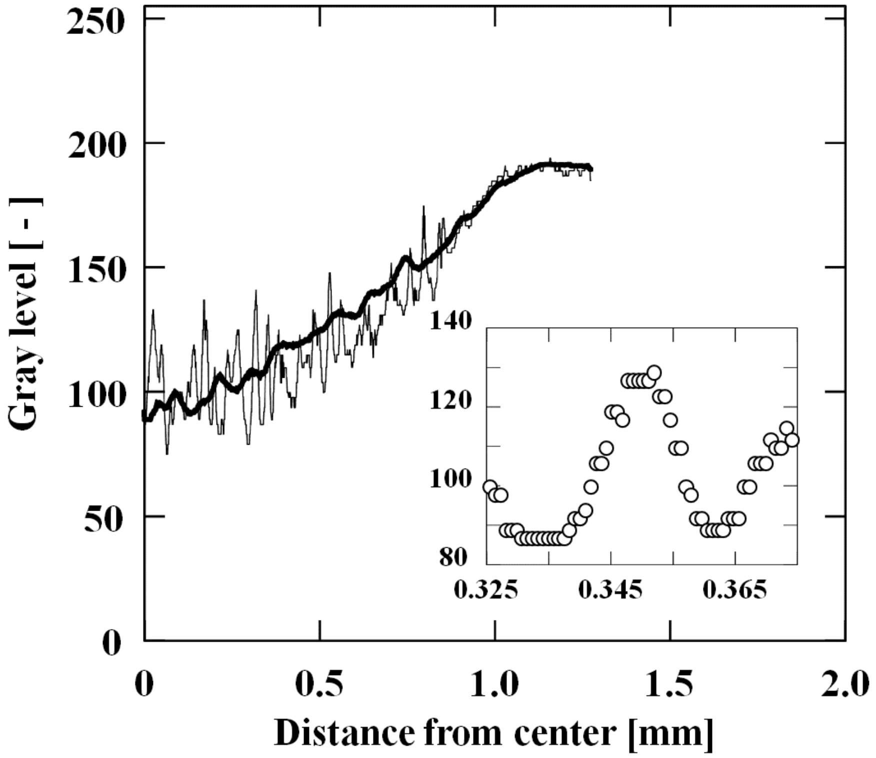

Fig. 3.

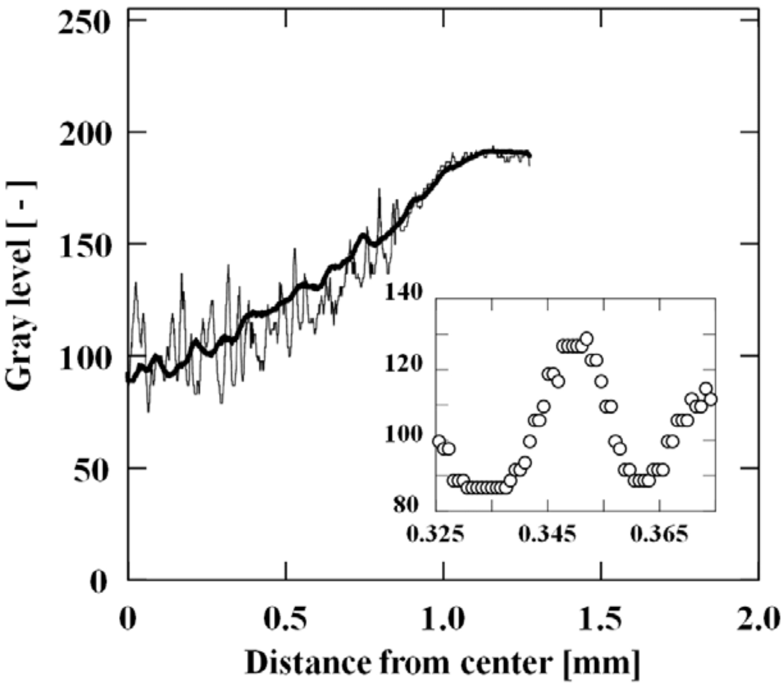
Gray level [-]
250
200
150
100
50
0
0
0.5
1.0
1.5
2.0
Distance from center [mm]
140
120
100
80
0.325
0.345
0.365

Fig. 4.

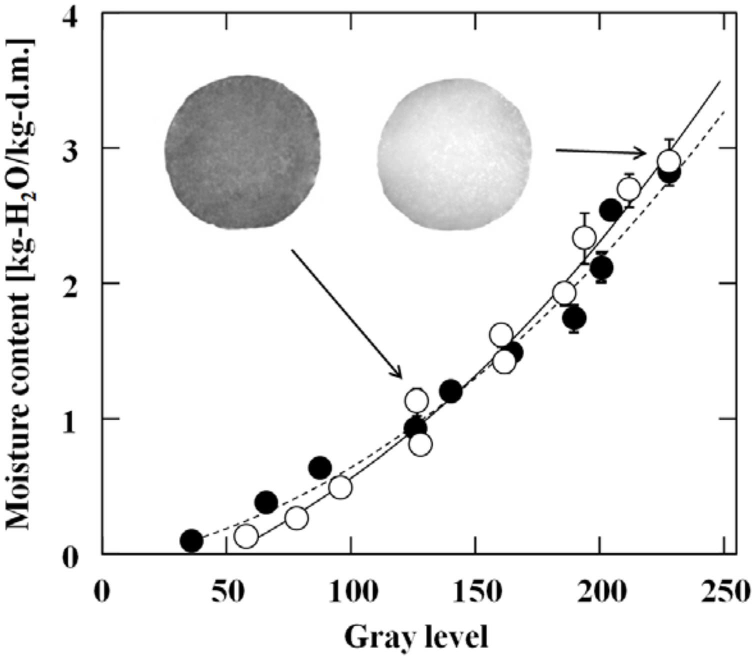
Moisture content [kg-H_2O/kg-d.m.]
4
3
2
1
0
0
50
100
150
200
250
Gray level

Fig. 5.

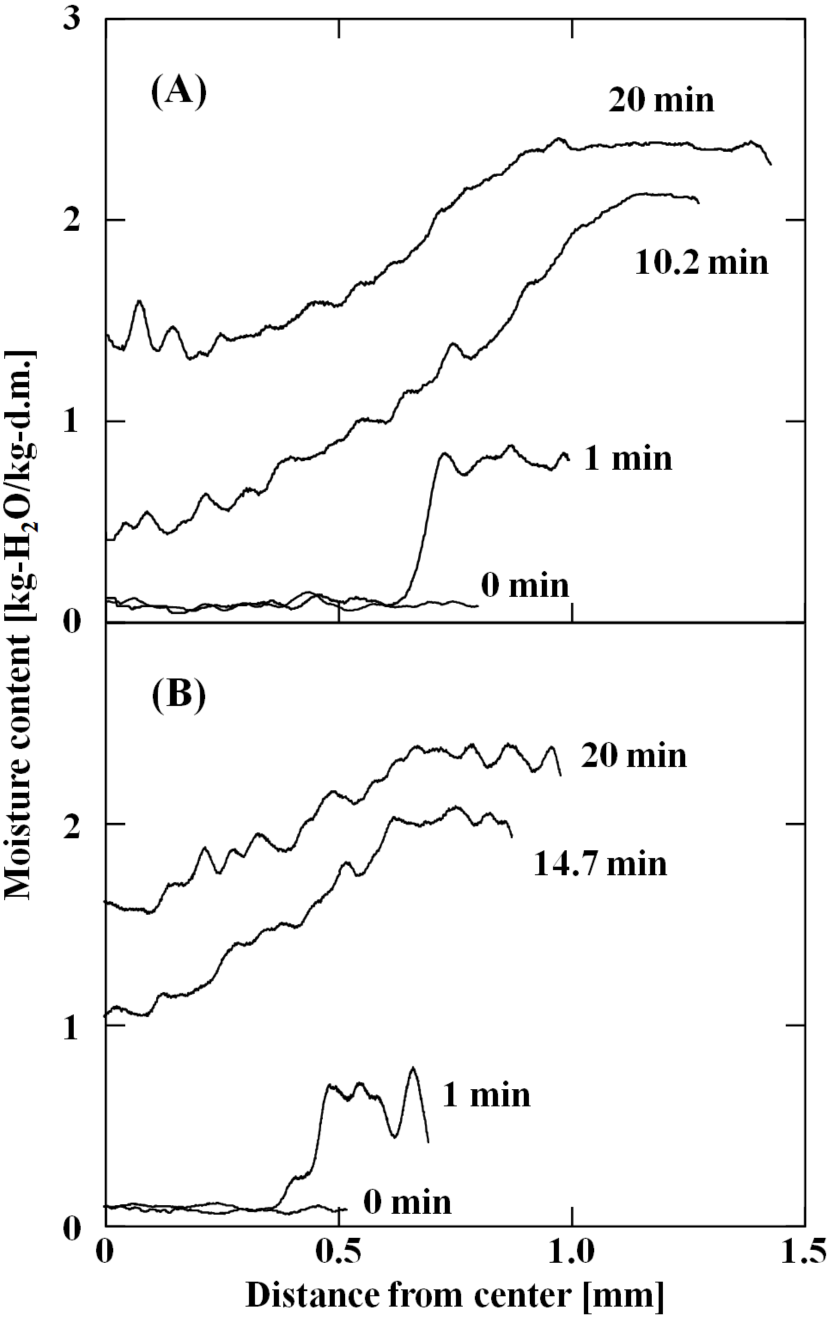
(A)
20 min
10.2 min
1 min
0 min
(B)
20 min
14.7 min
1 min
0 min
3
2
1
0
2
1
0
0
0.5
1.0
1.5
Moisture content [kg-H_2O/kg-d.m.]
Distance from center [mm]

Fig. 6.

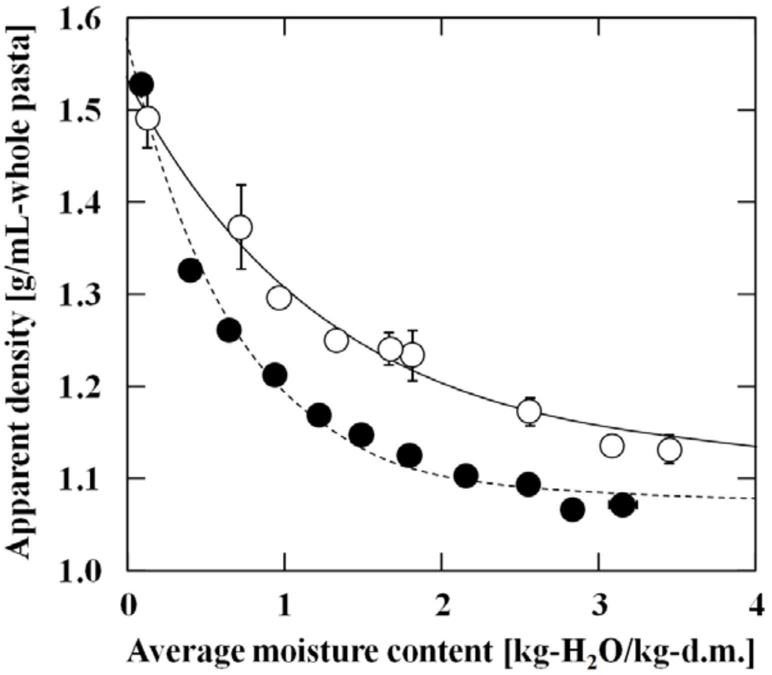
Apparent density [g/mL-whole pasta]
1.0
1.1
1.2
1.3
1.4
1.5
1.6
0
1
2
3
4
Average moisture content [kg-H2O/kg-d.m.]

Fig. 7.

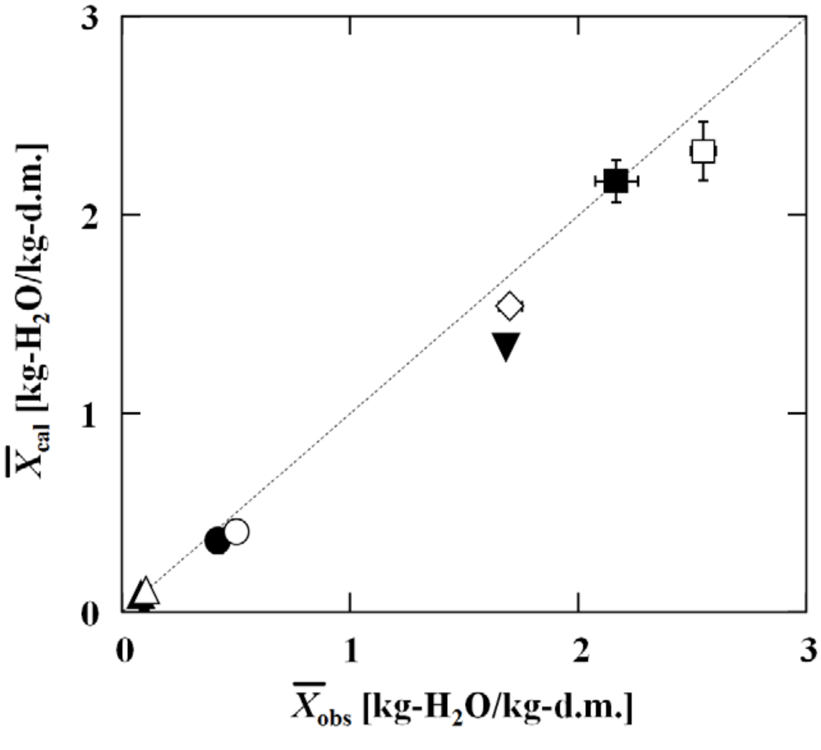
$\overline{X}_{cal}$ [kg-H2O/kg-d.m.]
0
1
2
3
0
1
2
3
$\overline{X}_{obs}$ [kg-H2O/kg-d.m.]

Fig. 8.

Corrigendum: Measurement of Moisture Profiles in Pasta during Rehydration Based on Image Processing

[*Food Bioprocess Technol.* (2014) 7:1465–1471]

Takenobu Ogawa • Shuji Adachi

Division of Food Science and Biotechnology, Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan

e-mail: adachi@kais.kyoto-u.ac.jp

We have recently become aware of two mistakes in our published paper *Food Bioprocess Technol.* (2014) 7:1465-1471 which should be corrected. However, these corrections do not alter the major results, discussion, and conclusions in the paper.

The first mistake is the spatial resolution of the proposed method. The spatial resolution in the original text should be corrected from “1.6 µm” to “3.2 µm” (page 1465, line 7 in the Abstract, page 1468, line 3 from the bottom in the section “Gray-Level Profile”, and page 1471, line 6 in the Conclusions). The pixel sizes of the acquired color images were 1.6 µm/pixel, as stated in the text (page 1467, line 31, below the section “Proposed Method”). The camera used is equipped with a filter that has a red, green, and blue mosaic pattern, therefore the spatial resolution of the proposed method using the blue images should be 3.2 µm. Please note that this correction to the spatial resolution does not detract from the novelty of the proposed method, because the values remain lower than those of the pitches of jaggy patterns of about 20 µm in the moisture profiles. As discussed in the section “Gray-Level Profile” in the original paper, these jaggy patterns can be ascribed to the nonuniformity of the starch gelatinization.

The second mistake is caused by an error in the computer program for processing the digital images to generate the blue images: unintended processing was done before pixilation. The error affects the series of figures relating to the images (Figs. 2-5 and 7) and the constants and correlation coefficients in the text. The corrections to the computer program have caused slight differences in Figs. 2, 4, and 7, and the numerical values in the text; there are also minor differences in the patterns in the gray level and moisture profiles in Figs. 3 and 5, respectively. Although the patterns become jaggier, these jaggy patterns do not change the above discussion. The non-uniform gelatinization of starch is more clearly displayed by this correction. The corrections to the numerical values in the text are as follows,

- Page 1469, line 4, below Eq. (8) should be replaced by “The constants *a*, *b*, and *c* were determined to best-fit the observed moisture contents to the calculated ones using the Solver of Microsoft Office Excel® 2010 and were 5.12×10^{-5}, 2.56×10^{-3}, and -2.20×10^{-1} for spaghettini, respectively, and

4.30×10^{-5}, 3.24×10^{-3}, and -8.08×10^{-2} for lasagna, respectively. The correlation coefficient (R^2) was 0.974 at minimum, indicating the accuracy of Eq. (8) and the validity of the proposed method."

- Page 1470, line 4 from the bottom in the section "Accuracy of Measurement" should be replaced by "The RMSE was 0.182 and 0.138 for spaghettini and lasagna, respectively, indicating the high accuracy of the proposed method for moisture content determinations in pasta."

In addition, the authors request correction to a misprint in a legend. This misprint was caused by inaccurate instructions from the authors at the proofreading stage. On page 1468, the legend for Fig. 2 should be replaced by "**Fig. 2** Cross-sectional images of the spaghettini rehydrated for 10.2 min (**A**) and the lasagna rehydrated for 14.7 min (**B**). (**a**) Original image and (**b**) digitally processed image. *Broken lines* show the segments of moisture profiles as an example"

The authors regret the need for corrections and would like to apologize for any inconvenience caused.

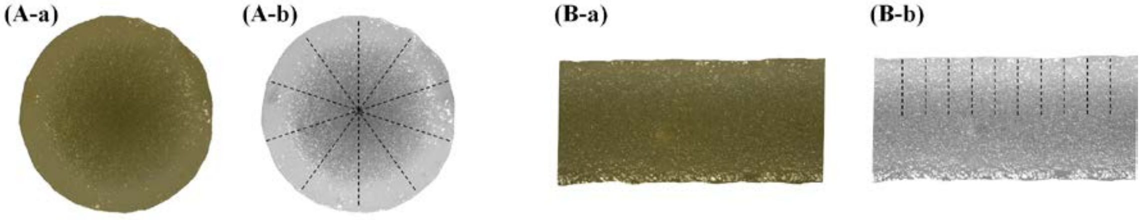

Fig. 2 Cross-sectional images of the spaghettini rehydrated for 10.2 min (**A**) and the lasagna rehydrated for 14.7 min (**B**). (**a**) Original image and (**b**) digitally processed image. *Broken lines* show the segments of moisture profiles as an example

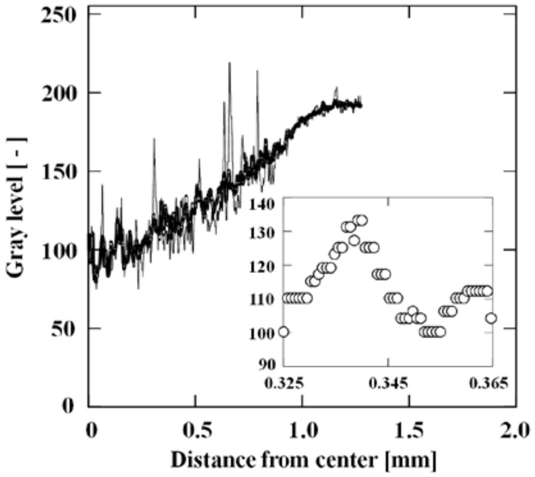

Fig. 3 Gray-level profile of the cross-sectional image of spaghettini rehydrated for 10.2 min. *Inset*: The extended profile

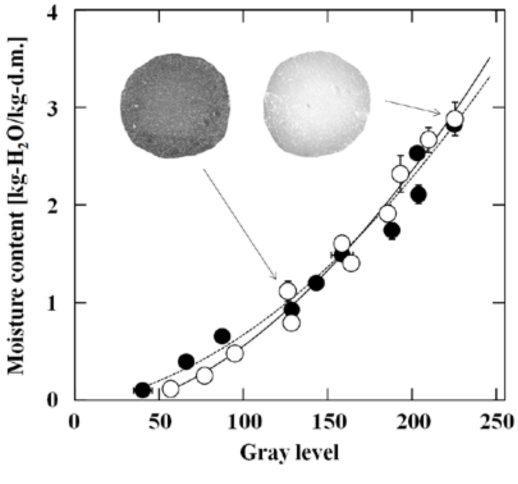

Fig. 4 Relationships between the moisture content and gray level in spaghettini (—○—) and lasagna (- -●- -) with homogeneous moisture distribution. *Bars* indicate standard deviation. The *pictures* in the figure are the digitally processed cross-sectional images obtained from spaghettini with homogenous moisture contents of 1.12 ± 0.02 and 2.89 ± 0.12 kg H_2O/kg d.m., indicated by *arrows*

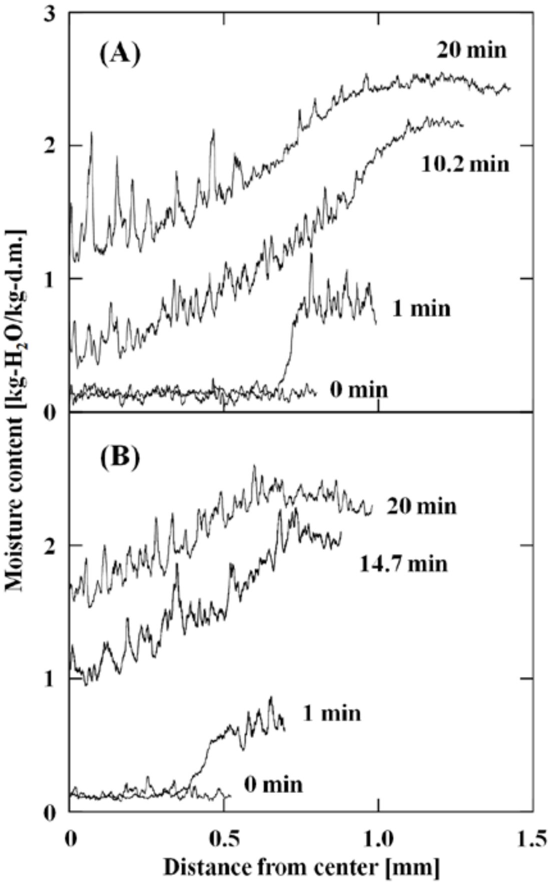

Fig. 5 Moisture profiles of spaghettini (**A**) rehydrated for 0, 1, 10.2, and 20 min and lasagna (**B**) rehydrated for 0, 1, 14.7, and 20 min, respectively

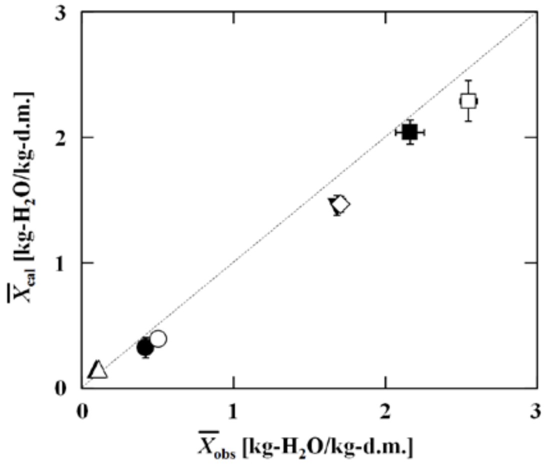

Fig. 7 Correlation between the experimentally observed average moisture content, $\overline{X}_{obs}$, and the moisture content calculated from the moisture profile, $\overline{X}_{cal}$, in spaghettini rehydrated for 0 min (*white up-pointing triangle*), 1 min (*white circle*), 10.2 min (*white diamond*), and 20 min (*white square*) and lasagna rehydrated for 0 min (*black up-pointing triangle*), 1 min (*black circle*), 14.7 min (*black down-pointing triangle*), and 20 min (*black square*). *Bars* indicating the standard deviation are *behind the symbols*