Temperature directly contributes to kernel development, such as grain filling and the rate of dry matter production in rice (Kobata and Uemuki, 2004). High temperature restricted the grain growth in rice (Inaba and Sato, 1976), wheat (Hawker and Jenner, 1993) and barley (Wallwork et al., 1998). They apprehended that these high temperature injuries were due to disappearance of enzyme activity relating to starch synthesis of the grains. Furthermore, Morita et al. (2005) reported that high night temperature (22/34°C, day/night) induced higher reduction of final grain weight and growth rate of rice in early- and mid-stage of grain filling along with the reduction of cell size compared with high day temperature (34/22°C, day/night). Moreover, the rice grain grown at 38/21°C temperature contained more chalky grains (Lisle et al., 2000). The chalky characteristics influenced shape, size and packing of amyloplasts in kernels, which were different from those in translucent grains. On the other hand, lower temperature also reduced the growth rate of grain, extended duration of the grain filling period and delayed grain maturation, although moderate cool temperature sometimes benefits grain yield (Yoshida, 1981; Egli, 1998; Shimono et al., 2002). It was shown that low temperature (18°C) produced defective and small endosperm grains of rice (Hong et al., 1995).

Temperature influences the period of rice grain maturation by changing the process of photosynthetic rate and dehydration (Hirotu et al., 2005). Modeling of grain water and dry matter against the thermal time during grain filling and maturation of winter wheat described the linear increase in dry matter of grains until a maximum size was attained at point of rapid decline of grain water (Pepler et al., 2006). Seed maturation is associated with numerous biochemical and physiological changes in tissues along with dehydration process of water. Since many metabolic processes such as enzymatic reaction, transportation and accumulation of ions occur in the cytosol of living tissues, water is considered to play vital roles in their physiological activities. Furthermore, the water compartments in seed correlated with the organic properties of macromolecular structures associated with seed development (Kano et al., 1990; Iwaya-Inoue et al., 2001). Generally, polysaccharides and proteins accumulate and store up during maturation of seeds accompanied with decreasing of water content and its...
mobility (Kano et al., 1990). Therefore, the physical states of water in plant cells reflect the cellular activity. The NMR allows nondestructive determination of changes in the states of water. Horigane et al. (2001) revealed the water distribution in developing rice grains by NMR microimaging. Spin-lattice relaxation time ($T_1$) and spin-spin relaxation time ($T_2$) are used as indicators of water status in biological tissues (Ishida et al., 2000; Chaughule et al., 2002; Iwaya-Inoue and Nonami, 2003). In our recent study, a close correlation was indicated by Nonami, 2003). In our recent study, a close correlation was observed in grains of rice grown in the outdoor (Ishibashi et al., 2004a, b). Moreover, $T_1$ and $T_2$ of water protons have been applied to the studies of higher plant tissues exposed to low/high temperatures such as 20, 25 and 30°C during grain maturation. We also discuss the profiles of NMR relaxation times in relation to kernel quality during development and maturation.

Materials and Methods

1. Plant materials

Rice seeds (Oryza sativa L. cv. Hinohikari) were sown in seed bed on 4th June 2004. Two seedlings were transplanted on 25 June in each plastic pots, sized 1/5000 a, and contained 2.5 kg soils. Plants were allowed to grow until heading stage at the experimental field of Kyushu University. Irrigation and pesticide were applied to ensure optimal plant growth. Compound fertilizer (N-P2O5-K2O:16-16-16) and ammonium sulfate (N:21%) at 0.6 and 0.5g were supplied to each pot, respectively, as basal dressing. Additionally, 0.3 g ammonium sulfate (N:21%) was topdressed at panicle formation and booting stages. The average mean air temperature was recorded 28.6°C at the experimental field until heading stage. On 27 August at the time of heading stage, all the pots were transferred to phytotron growth cabinet, and plants were grown there under three temperature treatments 20, 25 and 30°C until maturity. After flowering, at 7-8 days interval 4 pots were randomly selected from each treatment for analyzing necessary parameters. Grains (rough rice) of primary and the first (from top) secondary rachis branches were used for the required studies. Each experiment was replicated four times. All parameters were examined at seven stages, 7, 15, 22, 29, 36, 44 and 51 days after flowering (DAF). The pots were arranged in phytotron in complete randomized design.

2. $^{1}$H-NMR relaxation times and its analysis

Spin-lattice relaxation time ($T_1$) and spin-spin relaxation time ($T_2$) in the samples were measured based on the procedure described by Iwaya-Inoue et al. (2004a). A $^{1}$H-NMR spectrometer with a magnet operating at 25 MHz for $^1$H (M$^2$5A, JEOL Ltd., Tokyo, Japan) was used for the measurements of $T_1$ and $T_2$. Twenty to 24 grains (rough rice) were prepared for the measurements of NMR relaxation times. Sample was put into an NMR tube (10 mm in diameter) followed by setting in the NMR spectrometer. The probe temperature was controlled by thermostat connected to the sample chamber of the spectrometer at 30°C.

For $T_1$ measurements, the saturation recovery method (90°-τ-90° pulse sequence) was used. In this method, $T_1$ is determined from $M_1=M_0[1-exp(-τ/T_1)]$, where $M_1$ is the magnetization amplitude of proton at interval time $τ$, and $M_0$ is the magnetization amplitude of proton in the equilibrium state. In this experiment, free induction decay (FID) signal at every $τ$ was obtained by the accumulation of 4 scans. Forty-five $τ$ recovery times were logarithmically spaced between 3 and 600 ms. The repetition time of the sequence was always kept more than five times for $T_1$ of long fraction. The $T_2$ was measured by the Carr-Purcell-Meiboom-Gill (CPMG) method or solid echo method. $T_2$ is determined from $M_{2n}=M_0exp(-2nt/T_2)$, where $M_{2n}$ is the magnetization amplitude of the proton signal occurring at time $2τ$ after the initial 90° pulse in CPMG (90°-τ-180°y -2τ-180°y-2τ⋯) pulse sequence. The $T_2$ were calculated based on 500 echo signals acquired by accumulation of 16 scans. $τ$ was between 0.7 and 1.6 ms. The solid-echo (90°-τ-90°) method was also applied for $T_2$ measurements when $T_2$ values were below 1ms. $τ$ was 8μs. The solid echo signal of the seeds was obtained by accumulation of 128 scans. $M(t)=Σai×exp[-(t/T_2)^m]$ where $m$ is Weibull coefficient, and $ai$ is signal intensity in each fraction. The relative value of fraction ratio, ($f_0$) is calculated by a formula, $f_0=Σai/Σai$. The decay curve of echo signal was analyzed by using a non-linear least-square method on semi-log plots of signal intensity. For detailed analysis, two-component analysis was applied (Iwaya-Inoue et al., 2004a). For each treatment, four replications were used.

3. Water content and rice quality

Rice grains were oven-dried at 90°C for 20 h to determine the water content and dry weight (Ishibashi et al., 2004). Twenty to 24 grains were used for NMR at each sampling time. About 1000 husked grains of rice were used for evaluation of percent ripened grain and 100 kernels of the husked grains were evaluated for their quality. Total four replications were allocated in the present experiment. The ratio of ripened grain was assessed based on grain width of over 1.8 mm, and kernel quality was visually evaluated and scored according to Funaba et al. (1997).
Results

1. Influence of temperatures on dry-matter accumulation and water content of rice grains during maturation

Dry weight and water content of grains were measured under three temperature treatments, 20, 25 and 30°C, during rice grain maturation (Fig. 1). The dry weight of grains grown at 20°C linearly increased until 36 DAF, and thereafter it changed slightly (Fig. 1A). On the other hand, the dry weight of grains at 30°C linearly increased until 22 DAF and did not change significantly thereafter. Grains at 25°C indicated intermediate growth curve between the 20°C- and 30°C-treatment. The water contents of grains at 25°C and 30°C treatments markedly declined until 22 DAF, and gradually thereafter until harvest. At 51 DAF, the water contents of grains grown at 20°C were higher than those at 25°C and 30°C treatment. The water contents of grains at low temperature (20°C) were higher than those at higher temperatures except for the milky stage at 7 DAF.

2. Influence of temperatures on NMR relaxation times ($T_1$, $T_2$) in rice grains during maturation

The NMR spin-lattice relaxation time ($T_1$) and the spin-spin relaxation time ($T_2$), which denote the water
status, were measured in rice grains during the period of maturation under temperature treatments. $T_1$ and $T_2$ of long and short fractions were statistically analyzed by using a non-linear least-square method on semi-log plots of signal intensity. At 7 DAF, the $T_1$ values of long fraction in all temperature treatments were over 300 ms, and subsequently they declined to around 100 ms at 36 DAF (Fig. 2A). $T_1$ and $T_2$ values between 100 ms and 3 s are thought to show the existence of free water that mainly originates from vacuole water (Hills and Remigereau, 1997; Iwaya-Inoue and Nonami, 2003; Iwaya-Inoue et al., 2004a, b). The $T_1$ value of long fraction in grains grown at 20°C increased slightly from 7 to 15 DAF. Then, it gradually declined until 36 DAF and thereafter slightly increased. $T_1$ values in rice grain grown at 25°C were similar to those at 30°C. The $T_1$ values of short fraction in three temperature treatments at 7 DAF were between 60 and 80 ms. The $T_1$ value of short fraction in grains grown at 20°C increased from 7 to 15 DAF, and subsequently declined to around 25 ms at 36 DAF (Fig. 2B). The individual $T_1$ values of both long and short fractions in the grains grown at 20°C were higher than those in the grains at 25 and 30°C in whole periods except for milky stage.

On the other hand, $T_2$ values of long fraction in grains treated by three different temperatures were about 100 ms and were constant until 22 DAF (Fig. 3A). Abrupt $T_2$ decrease to less than 1 ms was observed in the grains grown at 25 and 30°C at 29 DAF. However, $T_2$ in the grains grown at 20°C was still over 100 ms at that day and it sharply decreased to less than 1 ms at 36 DAF. In all grains, $T_1$ values of long fractions were around 1 ms from 36 to 51 DAF. The $T_2$ values of short fractions in both grains grown at 25 and 30°C slightly decreased to less than 10 ms at 22 DAF and sharply to about 20 µs at 29 DAF (Fig. 3B). However, the $T_2$ value in the grains grown at 20°C did not change until 29 DAF and it dropped sharply to 20 µs at 36 DAF. Thus, the grains grown at 20°C showed markedly longer $T_2$ values than those grown at 25°C or 30°C at 29 DAF, which was the yellow-ripe stage. These results suggested that the grains grown at 20°C maintained free water for seven days longer than those grown at 25 and 30°C.

3. Variation of kernel quality caused by temperature stresses

Rice ears grown at each temperature were harvested at 51 DAF and left for air drying. Grains were threshed to kernels (brown rice). The percentage of ripened grains increased as the temperature rose; it was 59, 74 and 82% at 20, 25 and 30°C treatment, respectively (Table 1). Low temperature decreased ratio of ripened grains, while it increased the thousand grain weight.

| Temperature | Grains/pot | Ripened grain (%) | Thousand grain weight (g) |
|-------------|------------|-------------------|---------------------------|
| 20°C        | 968        | 58.9              | 21.4                      |
| 25°C        | 986        | 73.7              | 20.9                      |
| 30°C        | 1104       | 82.2              | 20.3                      |
To examine kernel quality seven types of kernels were scored based on visual observation (Funaba et al., 1997). The ratio of perfect kernels was highest (68%) at 25°C, followed by those at 20°C (27%) and 30°C (0%) (Fig. 4). In addition, notched-belly kernel was observed in 28% of the grains grown at 20°C while none of such kernels was observed in the grains at 30°C. However, the percentage of the grains with a white-back kernel greatly increased at a high temperature up to 85%.

Discussion

1. Relationship between NMR relaxation times ($T_1$, $T_2$) and water content in rice grains during maturation

$T_1$ values of long fraction in grains grown at three different temperatures were between 100 and 420 ms while those of short fraction were between 10 and 90 ms during developing and maturation stages (Fig. 2). It is considered that $T_1$ values between 100 ms and 3 s show the existence of free water, $T_1$ values of the long fraction over 100 ms mainly show the existence of free water and the $T_1$ of the short fraction shows the presence of loosely bound water (Hills and Remigereau, 1997; Iwaya-Inoue and Nonami, 2003; Iwaya-Inoue et al., 2004a, b). During milky and dough stages, 7 to 15 DAF, $T_1$ values of long and short fractions in rice grains grown at 20°C slightly increased while those in the grains grown at 30°C markedly decreased (Fig. 2). Histological studies on the development of endosperm in rice grains showed the transport of assimilates and water into the caryopsis during this stage (Hoshikawa, 1967, 1972). NMR microimaging clearly indicated that the fertilized kernels began to elongate rapidly after anthesis and reached the maximum length at 5 to 7 DAF, and an area with a striped pattern of high signal intensity was located on the surface of the endosperm of rice grains at 10 and 15 DAF (Horigane et al., 2001). Furthermore, they showed that water in caryopsis was mostly distributed along the peripheral layer and in the pericarp vascular bundle in the grains before 15 DAF (Horigane et al., 2001). Water content of rice grains gradually decreased during the ripening period although that of the grains grown at 20°C slightly increased at 15 DAF (Fig. 1A). These results suggest that the marked prolongation of $T_1$ value at 15 DAF in the grains grown at 20°C was due to immaturity of endosperm and its higher water content (Fig. 2). $T_1$ of both fractions in the grains grown at three different temperatures linearly decreased until 36 DAF. Thus, close relationship between $T_1$ and water content in rice grains was observed until 36 DAF. It was also shown that $T_1$ closely correlated with water content under low temperature stress in azalea buds (Kaku et al., 1984).

Slight prolongation of $T_1$ with decreasing water content was observed at 36 DAF in the rice grains grown at 20°C (Fig. 2) and in soybean seed at 52 DAF, which was the late maturing stage (Noda et al., 1998). A similar tendency was observed in sweet potato tubers exposed to cold stress and thus $T_1$ could not be solely ascribed to the water content when the mobility of water is restricted by macromolecules (Iwaya-Inoue et al., 2004b). In contrast, $T_1$ values of long and
short fractions in rice grains showed no significant decrease until 22 DAF but abrupt decrease at 29 DAF, yellow-ripe stage in the grains grown at 25 and 30°C. However, the values decreased at 36 DAF in the grains grown at 20°C (Fig. 3). \( T_2 \) values of long fraction in the grains at milky and dough stages were around 100ms showing the existence of free water (Chen and Gusta, 1978). \( T_2 \) values of the short fraction in the grains grown at 20°C were between 10 and 90 ms, and did not change until 29 DAF but dropped sharply to 20 \( \mu \)s at 36 DAF (Fig. 3). The \( T_2 \) value below 100 \( \mu \)s is considered to be associated with the presence of water tightly bound to macromolecules in cells (Hills and Remigereau, 1997; Iwaya-Inoue et al., 2004b). It has been stated that the grain tissues containing a small amount of water with low fluidity shows significantly short \( T_2 \) (Horigane et al., 2001). The transport of assimilates is associated with water movement in the grains. At yellow-ripe stage the decrease in water content was more emphasized in \( T_2 \) (Figs. 1B and 3). The starch in the endosperm of rice grains slowly changed from fluid to doughy along with decrease of water content and accumulation of transported assimilates during grain development. This change led to the solidification of endosperm and formation of translucent area (Horigane et al., 2001). These observations are in agreement with the results that water with high fluidity in the grains grown at either 25 or 30°C disappeared at yellow-ripe stage, and that free water in the grains grown at 20°C for a longer period than in the grains grown at a higher temperatures (Fig. 3).

2. Influence of temperatures on growth rate and kernel quality in relation to NMR relaxation times \( (T_1, T_2) \) of grains during maturation

The rate of dry matter accumulation until yellow-ripe stage was lower in the grains grown at 20°C than in those grown at higher temperatures (Fig. 1A). After harvest, the ratio of ripened grains grown at 20°C was the lowest though the thousand-grain weight was the highest (Table 1). Similar results were reported by Van Dobben (1962) and Chowdhury and Wardlaw (1978). It has been shown that low temperature (15 °C) prolonged grain maturation period of rice by lowering photosynthetic rate as well as delaying dehydration process (Hirotsu et al., 2005). Water status of seed correlated with the change in storage substances associated with seed development and maturation (Kano et al., 1990; Iwaya-Inoue et al., 2001). The present study indicated that the grains at 20°C maintained higher \( T_1 \) and \( T_2 \) values than those at 25°C and 30°C until yellow-ripe stage. The lower temperature reduces the rate of dry matter accumulation, extends duration of the grain filling period and delays grain maturation, although a modately cool temperature sometimes benefits grain yield (Yoshida, 1981; Egli, 1998; Shimono et al., 2002). The temperature of 20°C delayed starch accumulation and thus might maintain a water mobility for a long duration (Iwaya-Inoue et al., 2004b). Furthermore, many immature and notched-belly kernels were observed in rice grains grown at 20 °C (Fig. 4). It was reported that a low temperature (18 °C) produced defective and small endosperm grains in rice (Hong et al., 1995). Moreover, both immature and green kernels induced by 23°C were due to inhibition of carbohydrate uptake at early stage of kernel development (Nagato and Chaudhry, 1969). The notched-belly rice kernels also appeared in these grains because of partially stopped development of ventral radius.

In contrast, the grains grown at 30°C had no perfect kernels and had more than 85% white-back kernels (Fig. 4). The grains grown at 20 and 25°C had no white-back kernels. Rice plants exposed to 27 °C (mean air temperature) until 20 DAF produced a higher number of white-back kernels (Funaba et al., 1997). Morita et al. (2005) reported that both high night temperature (22/34°C day/night) and high day temperature (34/22°C day/night) significantly reduced the grain weight as well as the growth duration. Nagato and Chaudhry (1969) observed the depressed growth of cells and the starch accumulation on the dorsal sides of kernels at a high temperature. They suggested that it resulted in poor or insufficient accumulation of starch in dorsal ridges and thus enhanced to turn into opaque with whitish band in dorsal regions. It was indicated that high temperature stress (36/33°C) enhanced cell development of endosperm when the kernel has entered the linear phase of starch accumulation (Tashiro and Wardlaw, 1991). It has been stated that high temperature caused loosely packed starch granules, decreased kernel weight, and thus enhanced occurrence of abnormal and chalky rice kernels (Resurreccion et al., 1977; Lisle et al., 2000). Grains with white opaque parts in their cores or ventral sides of the endosperm, called white core rice kernel or white belly rice kernel, and have an unusual loose cell arrangement (Matsuda et al., 1988). The grains exposed to 30°C had significantly lower \( T_1 \) values than those exposed to 20°C and 25°C and heavier dry weight and lower water content until 22 DAF. Kano et al. (1990) stated that low molecular compounds reduce NMR relaxation times not so strongly at low concentrations but strongly at a higher concentration. The present study suggested that the early reduction of free water in grains at a higher temperature caused the formation of a higher number of white-back or chalky grains during maturation.
3. $T_1$ and $T_2$ are sensitive indicators of water content and dry matter accumulation in the grains during maturation under temperature stresses

In the present study, the changes in water mobility closely correlated with water content and dry matter accumulation in rice grains exposed to low/high temperature stresses. It was considered that the milky stage was sensitive to temperature and critical for determining the final size of endosperm (Hong et al., 1995). Both low and high temperatures influence grain growth rate, grain weight and kernel quality in rice and other cereals during grain filling stage (Hong et al., 1995; Lisle et al., 2000, Morita et al., 2005; Tahiri et al., 2005). NMR study revealed that free water in grains remained for a longer period at 20°C than at a higher temperature. The decrease in the NMR signal intensity in the endosperm of rice grains during the development of the caryopsis corresponded with the change in the physical property of the starch storage tissue from fluid to doughy, in appearance from milky white to translucent (Horigane et al., 2001).

These results clearly indicated that water proton relaxation times provide quantitative information on water status of rice grains exposed to temperature stresses. The changes in $T_1$ in rice grains closely related to the quantity of water until mid-mature stage while $T_1$ was more sensitive diagnostic indicator of dry matter accumulation at yellow-ripe stage in relation to temperature stresses.

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References

Chaughule, R. S., Mali, P. C., Patil, R. S., Joshi, G. D. and Lo, Y. M. 2002. Magnetic resonance spectroscopy study of sapota fruits at various growth stages. Innovative Food Sci. Emerging Technol. 3: 185-19.

Chen, P. M. and Gusta, L. V. 1978. Changes in membrane permeability of winter wheat cells following freeze-thaw injury as determined by Nuclear Magnetic Resonance. Plant Physiol. 61: 878-882.

Chowdhury, S. I. and Wardlaw, I. F. 1978. The effect of temperature on kernel development in cereals. Aust. J. Agric. Res. 29: 205-223.

Egli, D. B. 1998. Seed biology and the yield of grain crops. CAB Int., Oxford, UK.

Funaba, M., Nishimura, K. and Izumi, S. 1997. Study on cropping season of rice plants in Nagasaki Prefecture. IV. Deterioration of quality of brown rice under high temperature during ripening period. Rep. Kyushu Br. Crop Sci. Soc. Japan 63: 15-17.

Hawker, J. S. and Jenner, D. F. 1993. High temperature affects the activity of enzymes in the committed pathway of starch synthesis in developing wheat endosperm. Aust. J. Plant Physiol. 20: 197-209.

Hills, B. P. and Remigereau, B. 1997. NMR studies of changes in subcellular water compartmentation in parenchyma apple tissue during drying and freezing. Int. J. Food Sci. Technol. 32: 51-61.

Hirotsu, N., Makino, A., Yokota, S. and Mae, T. 2005. The photosynthetic properties of rice leaves treated with low temperature and high irradiance. Plant Cell Physiol. 46: 1377-1383.

Hong, S. K., Aoki, T., Kitano, H. and Nagato, Y. 1995. Temperature-sensitive mutation, embryoless 1, affects both embryo and endosperm development in rice. Plant Sci. 108: 165-172.

Horigane, A. K., Engelaar, W. M. H. G., Maruyama, S., Yoshida, M., Okubo, A. and Nagata, T. 2001. Visualisation of moisture distribution during development of rice caryopses (Oryza sativa L.) by nuclear magnetic resonance microimaging. J. Cereal Sci. 33: 105-114.

Hoshikawa, K. 1967. Studies on the development of endosperm in rice. 2. Process of endosperm tissue formation with special reference to the enlargement of cell. Jpn. J. Crop Sci. 36: 203-209.

Hoshikawa, K. 1972. Anatomical and developmental studies of the rice endosperm tissue. Biol. Sci. 23: 66-76.

Inaba, K. and Sato, K. 1976. High temperature injury of ripening in rice plant. VI. Enzymes activities of kernel as influenced by high temperature. Proc. Crop Sci. Soc. Jpn. 45: 162-176.

Ishibashi, Y., Sueyoshi, R., Morita, T. and Iwaya-Inoue, M. 2004. Response of molecular dynamics of water in seed dormancy and germination. Cryobiol. Cryotechnol. 50: 63-69.

Ishibashi, Y., Sueyoshi, R., Morita, T., Yoshimura, A. and Iwaya-Inoue, M. 2005. Detection of pre-harvest sprouting in rice seeds by using $^1$H-NMR. Environ. Control Biol. 43: 131-137.

Ishida, N., Koizumi, M. and Kano, H. 2000. The NMR microscope: a unique and promising tool for plant science. Ann. Bot. 86: 259-278.

Iwaya-Inoue, M., Kumamoto, Y. and Watanabe, G. 2001. Ratio changes in Lorentzian/Gaussian curves determined by $^1$H-NMR reflect seed dehydration. Cryobiol. Cryotechnol. 47: 51-56.

Iwaya-Inoue, M. and Nonami, H. 2003. Effects of trehalose on flower senescence from the viewpoint of physical states of water. Environ. Cont. Biol. 41: 3-15.

Iwaya-Inoue, M., Matsui, R. and Fukuyama, M. 2004a. Cold- or heat-tolerance of leaves and roots in perennial ryegrass determined by $^1$H-NMR. Plant Prod. Sci. 7: 118-128.

Iwaya-Inoue, M., Matsui, R., Sultana, N., Saitou, K., Sakaguchi, K. and Fukuyama, M. 2004b. $^1$H-NMR method enables early identification of degeneration in the quality of sweet potato tubers. J. Agron. Crop Sci. 190: 65-72.

Kaku, S., Iwaya-Inoue, M. and Gusta, L. V. 1984. Relationship of nuclear magnetic resonance relaxation time to water content and cold hardiness in flower buds of evergreen azaleas. Plant Cell Physiol. 25: 875-882.

Kano, H., Ishida, N., Kobayashi, T. and Koizumi, M. 1990. $^1$H-NMR imaging analysis of changes of free water distribution in barley and soybean seeds during maturation. Jpn. J. Crop Sci. 59: 503-509.

Kobata, T. and Uemuki, N. 2004. High temperatures during the grain-filling period do not reduce the potential grain dry
matter increase of rice. Agron. J. 96: 406-414.
Lisle, A. J., Martin, M. and Fitzgerald, M. A. 2000. Chalky and translucent rice grains differ in starch composition and structure and cooking properties. Cereal Chem. 77: 627-632.
Maheswari, M., Joshi, D. K., Saha, R., Nagarajan, S. and Gambir, P. N. 1999. Transverse relaxation time of leaf water protons and membrane injury in wheat (Triticum aestivum L.) in response to high temperature. Ann. Bot. 84: 741-745.
Matsuda, T., Yamamoto, Y. and Chouman, N. 1988. The change of fine structure in rice grains during cooking. Jpn J. Crop Sci. 57 (Extra. 1): 214-215*.
Morita, S., Yonemaru, J. and Takanashi, J. 2005. Grain growth and endosperm cell size under high night temperatures in rice (Oryza sativa L.). Ann. Bot. 95: 695-701.
Nagato, K. and Chaudhry, F. M. 1969. Ripening of japonica and indica type of rice as influenced by temperature during ripening period. Proc. Crop Sci. Soc. Jpn. 38: 657-665.
Noda, N., Sakaguchi, K., Kumamoto, Y. and Iwaya-Inoue, M. 1998. Determination of the phase change in the $^1$H-NMR relaxation behavior of dehydrating soybean seed using the AIC method. J. Fac. Agr. Kyushu Univ. 43: 67-74.
Pepler, S., Gooding, M. J. and Ellis, R. H. 2006. Modeling simultaneously water content and dry matter dynamics of wheat grains. Field Crops Res. 95: 49-63.
Resurreccion, A. P., Hara, T., Juliano, B. O. and Yoshida, S. 1977. Effect of temperature during ripening on grain quality of rice. Soil Sci. Plant Nutr. 23: 109-112.
Shimono, H., Hasegawa, T. and Iwama, K. 2002. Response of growth and grain yield in paddy rice to cool water at different growth stages. Field Crops Res. 73: 67-79.
Tahir, I. S. A., Nakata, N. and Yamaguchi, T. 2005. Responses of three wheat genotypes to high soil temperature during grain filling. Plant Prod. Sci. 8: 192-198.
Tashiro, T. and Wardlaw, I. F. 1991. The effect of high temperature on kernel dimensions and the type and occurrence of kernel damage in rice. Aust. J. Agric. Res. 42: 485-496.
Van Dobben, W. H. 1962. Influence of temperature and light conditions on dry-matter distribution, development rate and yield in arable crops. Neth. J. Agric. Sci. 10: 377-389.
Wallwork, M. A. B., Logue, S. J., MacLeod, L. C. and Jenner, C. F. 1998. Effects of high temperature during grain filling on starch synthesis in developing barley grain. Aust. J. Plant Physiol. 25: 173-181.
Yoshida, S. 1981. Fundamentals of Rice Crop Science. IRRI, Los Baños, Philippines.

* In Japanese.