Magnetic resonance imaging studies to determine the moisture removal patterns in wheat during drying

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Ghosh, P.K., Jayas, D.S., Gruwel, M.L.H. and White, N.D.G. 2006. **Magnetic resonance imaging studies to determine the moisture removal patterns in wheat during drying**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 7.13-7.18. Non-invasive Magnetic Resonance Imaging (MRI) was used to study the moisture removal pattern inside a single grain of wheat (cultivar: A.C. Barrie) during drying. Images were obtained using a conventional spin-echo pulse sequence on an 11.7 Tesla MR spectrometer equipped with a drying apparatus. Samples of intact kernels (with all three components: pericarp, embryo, and endosperm), mechanically scarified kernels, and kernels with the embryo-removed were dried at different temperatures to study the influence of kernel components on the internal moisture removal and distribution pattern. MR images were recorded at equal time intervals and moisture patterns were analyzed from the MR images of wheat kernels. Analysis of the images revealed that moisture loss from the seed parts differed significantly during drying and was dependent upon the grain components. **Keywords:** drying, MRI, wheat, moisture distribution, gradient vector.

L'imagerie par résonance magnétique non invasive (IRM) a été utilisée pour étudier le profil de teneur en eau à l'intérieur de grains de blé individuels (cultivar : A.C. Barrie) durant le séchage. Les images ont été obtenues en utilisant un séquenceur conventionnel à pulsation spin-echo sur un spectromètre 11.7 Tesla MR équipé d'un appareil de séchage. Des échantillons de grains intacts (avec les trois composantes : péricarpe, embryon et endosperme), de grains scarifiés mécaniquement et de grains dont l'embryon avait été enlevé ont été séchés à des températures différentes pour étudier l'influence des composantes des grains sur la diminution de l'humidité interne et les profils d'humidité ont été analysés à partir d'images RM des grains de blé. L'analyse des images a révélé que la perte d'humidité des composantes du grain était significativement différente durant le séchage et était dépendante des composantes du grain. **Mots clés**: séchage, IRM, blé, distribution d'humidité, vecteur gradient.

INTRODUCTION

Proper moisture conditions are important for safe grain storage and handling. Movement of the water inside the grain kernels plays an important role during drying. Drying is a complex process of simultaneous heat and moisture (mass) transfer. Most of the previous works on drying models (Luikov 1966; Husain et al. 1973; Sokhansanj and Gustafson 1980; Sokhansanj and Bruce 1987; Haghighi and Segerlind 1988; Haghighi et al. 1990; Czaba and Neményi 1997) have assumed one or more of the following mechanisms: capillary flow, liquid diffusion, surface diffusion, vapor diffusion, thermal diffusion, or hydrodynamic flow to analyze simultaneous heat and mass transfer phenomena. The grain drying models presented in the literature were derived under a number of assumptions made to simplify these models for computation. All of the published models have assumed that the moisture content distribution is uniform in a kernel at the beginning of drying and that the moisture removal from the kernels is uniform during drying. However, these simplifications do not represent the reality as has been demonstrated by published studies of moisture distribution using magnetic resonance imaging (MRI) and therefore may reduce the accuracy of the model prediction. Magnetic resonance imaging is a non-destructive and non-invasive technique that is used to determine the moisture distribution inside intact kernels. The MRI method can enhance understanding of the underlying mechanism of the grain drying process on a single kernel, which would help in developing accurate grain drying models with well-defined initial and boundary conditions.

Magnetic resonance imaging uses radio waves and powerful magnets to generate images of tissue. A strong magnetic field partially aligns the hydrogen atoms of water molecules in the tissue. A radio wave then disturbs the built-up magnetization, and radio waves are in turn emitted as the magnetization returns to its starting location. These radio waves are detected and used to construct an image. Ghosh and Jayas (2004) have extensively reviewed the recent research developments of MRI techniques and its potential in solving various grain related research problems. Magnetic resonance imaging can be used to obtain two or three-dimensional moisture transfer profiles inside a single grain kernel during drying. Little work has been carried out to determine transient moisture distribution inside the grain kernels during the drying process. The first experiment of this kind was reported by Song and Litchfield (1990) who determined the transient moisture profiles of ears of corn based on image pixel intensities at different drying times. Moisture distribution and changes inside the corn were distinctly different and non-uniform during the drying process. Song et al. (1992) visually examined a series of MR image sequences to investigate moisture transfer and distribution from and within a corn kernel during drying at 27 and 49°C. It was determined that moisture distribution in the kernels was non-uniform. Moisture loss also differed significantly during drying through two primary routes, the glandular layer of the scutellum and the pericarp. Kovács and Neményi (1999) used MR images of corn kernels during drying at 46°C and performed moisture gradient vector analysis to demonstrate the pathways of the moisture loss from the intact kernel during drying. They also found non-uniform distribution of moisture inside the intact kernel before and during drying. Moisture was lost faster from the endosperm than the pericarp and it was the slowest from the scutellum. Ghosh et al. (2004) have first reported an explanation of moisture movement from the MR images of wheat kernels during drying. This study revealed the anisotropic and non-uniform nature of moisture distribution and migration prior-to or during drying of intact-wheat kernels. They observed that moisture loss was faster from the pericarp and endosperm compared to the germ with an increase in drying time. These conditions are an important consideration to develop accurate grain drying models. However, no efforts have been made so far to determine the effects of grain structural components on the movement of moisture from the grain kernels during drying using MRI. Therefore, the objectives of this study were to assess the effect of the structural components of wheat on the movement of moisture during drying using MRI and to study the movement of moisture inside the wheat kernel from the moisture gradient vectors calculated from each pixel of the subtraction of MRI images.

MATERIALS and METHODS

Drying experiments

The wheat kernels (*Triticum aestivum* L., cv. A.C. Barrie) used in this study were procured from the Cereal Research Centre of Agriculture and Agri-Food Canada, Winnipeg. Individual kernels (approximately ellipsoidal shaped, 6 mm long and 3 mm diameter) were glued inside a small glass tube (12 mm long and 7 mm outer diameter) which was inserted into the probe (Helmholtz configuration) and then the probe was placed into the bore of the MRI magnet. The grain kernels were subjected to a regulated low flow (0.23 m/s) of pre-heated N_2 (40 and 50ºC ±1ºC) during the intact drying process while MR images were obtained. Each drying experiment was continued for 4 h. For each temperature, three different kernels were used for measurements that gave similar results but these can not be averaged because of different kernel sizes. Therefore, a representative image for each treatment was analyzed and discussed. The selected low flow rate of nitrogen was high enough to ensure internally controlled drying. Nitrogen flow was parallel to the long axis of the wheat kernel. The wheat kernels were preconditioned to selected moisture content (20 to 64% w.b.) by the static equilibrium moisture content method (Solomon 1951) or by imbibition in distilled water for 12-18 h at the beginning of every MR imaging experiment. The wheat kernels with no trace of germination were selected for this study. The initial moisture content of the wheat kernels was determined by the standard air-oven method (ASAE 2004) at the beginning of every MR imaging experiment. Wheat kernels with a high moisture level (>20%) were used in this study to acquire bright MR images which helped in studying the intrinsic details. To test the influence of kernel parts on moisture movement within the grain, mechanical scarification was achieved by either making an incision in the pericarp before starting each experiment, or removing the germ end from the kernel before moisture equilibration. The germ-removed kernels were at a lower moisture content (37%) than the intact kernels (64%).

MRI data acquisition

All MR images were obtained using a 11.7 T (500 MHz) Magnex (Magnex Scientific Ltd., Yarnton, UK) super-conducting vertical bore magnet equipped with a Magnex SGRAD 123/72/S 72 mm self-shielded, water-cooled, gradient set capable of producing a maximum gradient strength of 550 mT/m located at the National Research Council of Canada's Institute for Biodiagnostics, Winnipeg, Manitoba. A Bruker (Milton, ON) Avance spectrometer with a ParaVision v.2.1.1 operating system was interfaced to the magnet to record and analyze the images. A conventional three-dimensional multi-slice Hahn spin-echo pulse sequence (Hahn 1950) was used for the MRI data acquisition. Images were processed as 8-bit, in a 128 x 64 x 8 matrix with a field-of-view of 12.8 x 12.8 x 4 mm, resulting in a pixel resolution of 100 μm x 200 μm x 500 μm. The MR Image size was increased by zero filling. Based on a compromise between image contrast and imaging time, the repetition time, TR, and the echo time, TE, were set to 200 ms and 3.375 ms, respectively. MRI data were acquired continuously and saved every 10 min 18 s without interrupting the drying process. During this time, six scans were acquired for signal averaging. A total of eight ^{1}H density image slices, each of 0.5 mm thickness, were obtained from each wheat kernel.

MRI data processing

The acquired MR images were gray-scale representations of the number of protons in the water-containing parts of the wheat kernels, which in turn represents water distribution. The brighter the image, the greater the number of protons. The darker the image, the fewer the number of protons. Multi-slice MR image data were scaled with respect to the first image of the series, and displayed using Marevisi v. 7.1 (Institute for Biodiagnostics, National Research Council Canada, Winnipeg, MB) and NIH's public domain Java image processing program ImageJ (http://rsb.info.nih.gov/ij/). Image analysis (image acquiring and subtraction, gradient vector calculation and visualization) was performed with Matlab v. 7, R14 (The Mathworks, Natick, MA).

RESULTS and DISCUSSIONS

The representative MR images of sequential slices (2D) from MRI data sets (3D) collected as a function of time of an intact wheat kernel (approx. 20% w.b.) after every 1 h of drying at 50ºC is shown in Fig. 1. A particular transverse slice was selected (slice number 6) to best illustrate the moisture distribution in the kernel with the greatest anatomical detail. The Signal-to-noise ratio (SNR) of the first image (t = 0) in serial MR images of Fig. 1 was 8.32. The SNR was calculated as the ratio of average pixel intensity of a region of interest (ROI) in the whole grain to the average pixel intensity of the same size area in a region of noise only. The brighter portion represented higher moisture content, and overall signal intensity decreased with time. The moisture movement within the wheat kernel during drying was studied as a function of drying time. The images clearly showed that the non-uniform pattern of moisture distribution inside the intact-wheat kernel was present before drying was started and continued during drying. The lowest moisture content occurred in the endosperm. The highest water content was detected in the embryo. The crease of the kernel also looked bright at the beginning of drying. The probable reason could be that some water molecules adhered to the surface of the

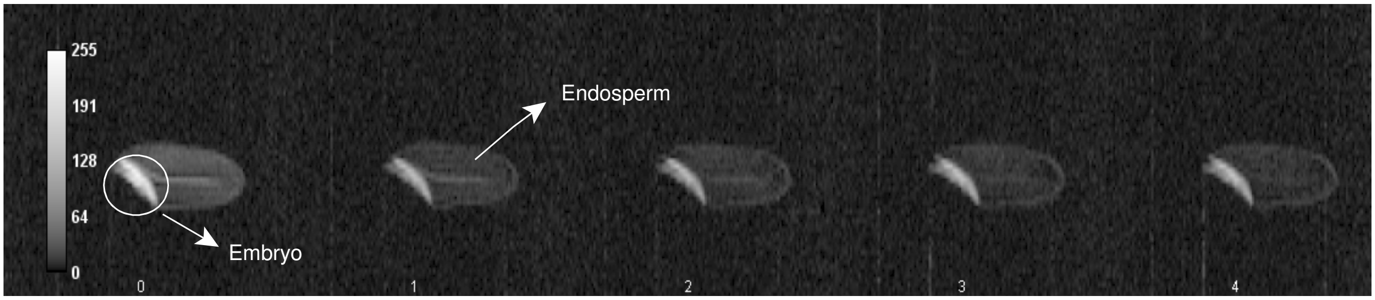


Fig. 1. MRI images of an intact wheat kernel during drying at every hour. Drying conditions: temperature, 50ºC; drying time, 4 h. Numbers at the bottom of the images indicate the time, in hours, from the beginning of drying.

crease by the surface tension during wheat conditioning. The images also revealed that moisture loss was faster from the pericarp because MR signal intensities in the pericarp region could not be measured as drying of this area occurred fast with respect to the time resolution of the experiment. The moisture loss from the endosperm was more compared to the embryo, which was evident from the inner part of the embryo that remained at high moisture content even after 4 h drying.

We conducted 2D Gradient Vector analysis, in Matlab, to describe the real moisture loss from each point of the whole-wheat kernel images. The Matlab computed gradient of a function of two variables, $I(x,y)$, and is defined as:

$$\nabla I = \frac{\partial I}{\partial x}\hat{i} + \frac{\partial I}{\partial y}\hat{j} \tag{1}$$

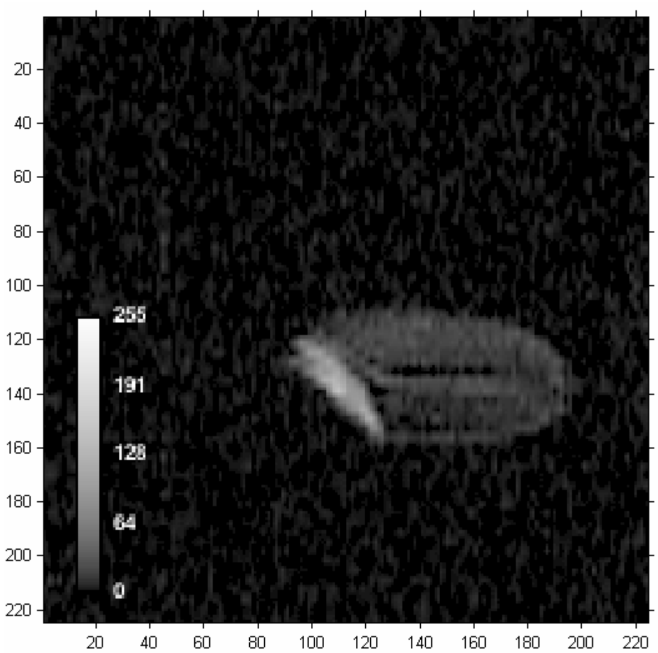
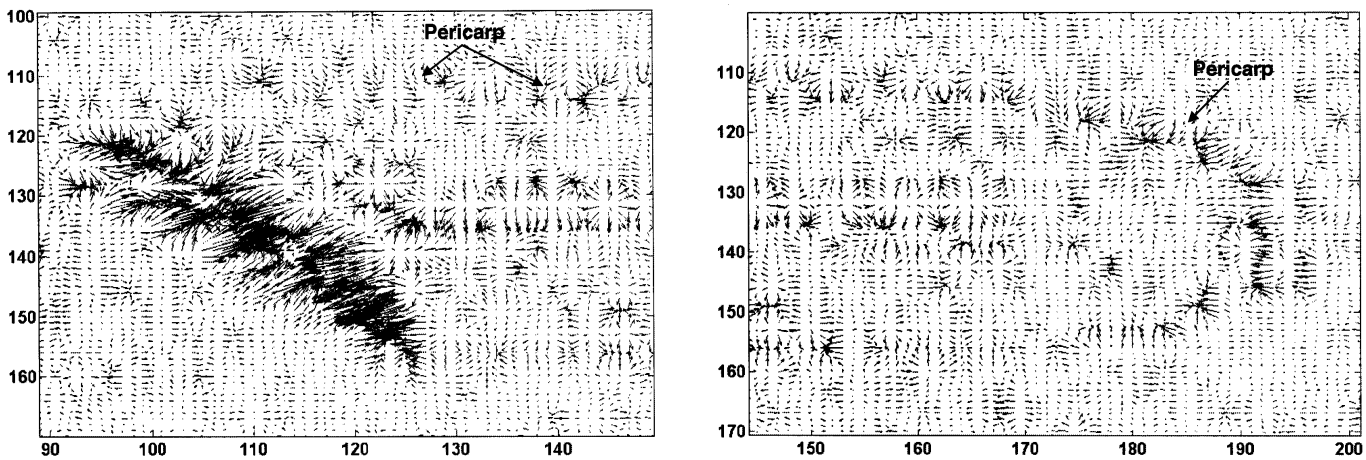


Fig. 2. Subtracted image of an intact-wheat kernel (after 1 h of drying) obtained from Fig. 1. The scales show the pixels and the sidebar in the image represents the moisture contents in terms of the grayscale intensity; high gray values represent high moisture contents than the low gray value parts.

The gradient can be thought of as a collection of vectors pointing in the direction of increasing values of I. In our case, I is the subtracted image matrix, and x and y are the pixel coordinates. Figure 2 shows the subtracted image of the first (before drying) and second (after 1 h of drying) images of an intact wheat kernel shown in Fig. 1. The gradient vectors of the moisture loss data for the subtracted image are shown in Fig. 3. The longer the vectors the faster the moisture level changes. The rates of moisture change in the pericarp, endosperm, and embryo during drying were clearly different. The rate of moisture loss was slower from the endosperm region, whereas the pericarp region dried faster at the initial stages of drying. The fastest moisture decrease was from the outermost layer of the embryo section as its gradient vectors are the largest and pointing outwards from the kernel but the inner vectors show inward movement. The vectors at the transition region of embryo and endosperm show inward movement in the direction of the embryo. This typical direction of arrowheads indicates that the water has the tendency to move from the endosperm towards the germ (embryo) through the fingerlike cells of the scutellum epithelium (the outer layer of the scutellum located next to the endosperm) which functions as an absorption organ. This explains why the embryo was able to retain more moisture even after 4 h of drying. Kovács and Neményi (1999) reported a similar effect on moisture removal in corn kernels during drying.

For the mechanically scarified kernels (approximately 64% w.b.) and embryo-removed kernels (approximately 37% w.b.), the representative images are shown in Figs. 4a and 4b. The SNRs of the first images (t = 0) in serial MR images of Figs. 4a and 4b were 47.9 and 18.2, respectively. The fifth and sixth slices were chosen in Figs. 4a and 4b, respectively, to evaluate the moisture transfer during drying. Gradient vectors were calculated and visualized to determine the moisture removal pattern in both type of grains to test if the site of superficial cutting of pericarp and the removal of embryo influenced the moisture movement in kernels. Figures 5 and 7 show the subtracted images of the first (before drying) and second (after 1 h of drying) images of a mechanically scarified kernel and an embryo-removed kernel, respectively. Figures 6 and 8 show the gradient vectors of the 2D moisture movement obtained from Figs. 5 and 7 for the mechanically damaged kernels and the embryo-removed kernels, respectively. It can be seen from Fig. 6 that vectors from the embryo end are directed towards the endosperm section and the amplitude of the vectors is long. Long arrows are also detected at the incision-part of the pericarp



(a) (b)

Fig. 3. Gradient vectors of the subtracted image matrix of Fig. 2: (a) shows the embryo and part of endosperm region; and (b) shows the endosperm region. The arrows indicate the moisture movement from each point; the arrow size is proportional to the rate of moisture loss.

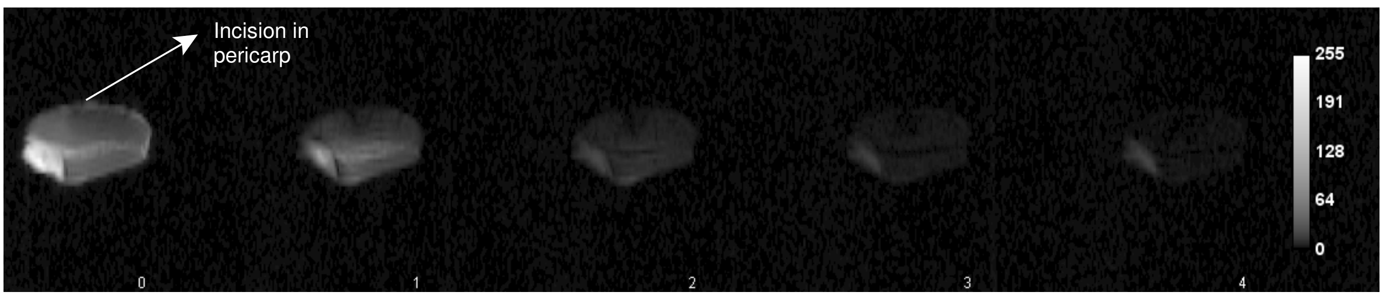


Fig. 4(a). MRI images of a mechanically scarified wheat kernel during drying at every hour. Drying conditions: temperature, 40ºC; drying time, 4 h. Numbers at the bottom of the images indicate the time, in hours, from the beginning of drying.

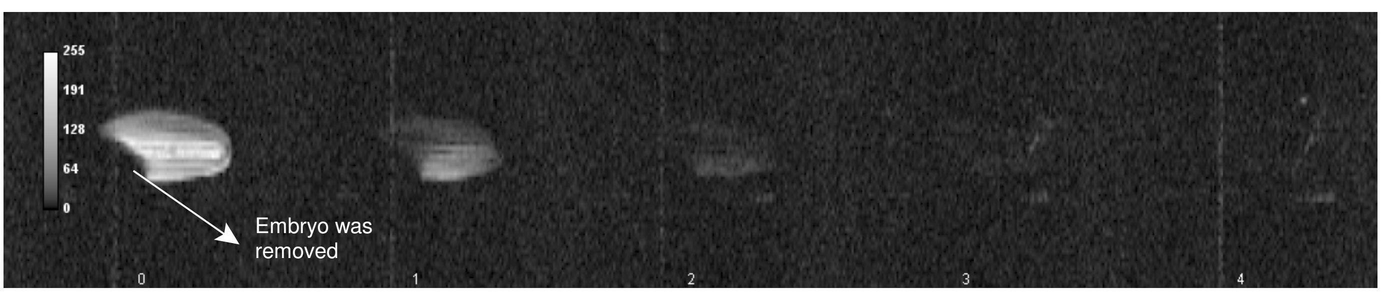


Fig. 4(b). MRI images of an embryo-removed wheat kernel during drying at every hour. Drying conditions: temperature, 50ºC; drying time, 4 h. Numbers at the bottom of the images indicate the time, in hours, from the beginning of drying.

region that tend towards outward direction of the kernel. It is assumed that when incision in the pericarp was done, the outer pericarp layers of wheat (epidermis and hypodermis) as well as the inner layers of the pericarp were broken. Moreover, the inner layers of the pericarp consist of thinner walled cross-cells and tube-cells containing intercellular spaces through which water could move rapidly. Therefore, water was released relatively faster from the scarified regions of the pericarp. This means the pericarp plays an important role in moisture movement inside the grain during drying. Intact pericarp behaves as an insulator after the initial stages of drying and resists the movement of water from the kernel. However, a damaged pericarp allows moisture to move from the kernel. In the case of embryo-removed kernels, moisture moved out in a uniform manner from the wheat kernel as the outermost vectors tend towards the environment but one layer deeper the arrows show inward movement (Fig. 8). When the germ was removed from the wheat kernel, the water moved uniformly through the capillaries

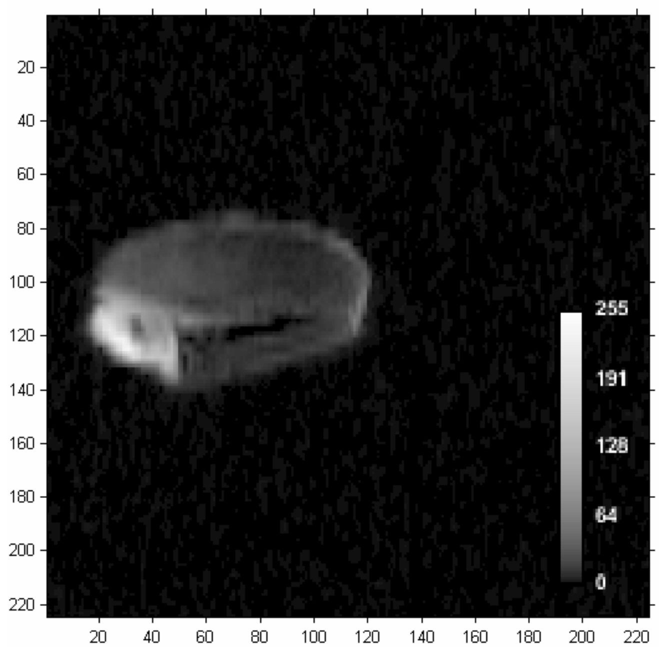


Fig. 5. Subtracted image of a mechanically scarified kernel (after 1 h of drying) obtained from Fig. 4(a). The scales show the pixels and the sidebar in the image represents the moisture contents in terms of the grayscale intensity; high gray values represent high moisture contents than the low gray value parts.

of the endosperm towards the large rectangular aleurone layer of the endosperm. The aleurone layer is the outermost layer of the endosperm, which is attached to the innermost paricarp layer of the wheat kernel. Once the water comes to the aleurone layer of the endosperm, it then moved out from the wheat kernel through the intercellular spaces of the pericarp. Arrows showing inward movement would be arising due to the inner bran layers (the aleurone) high in protein and the outer bran layer (pericarp,

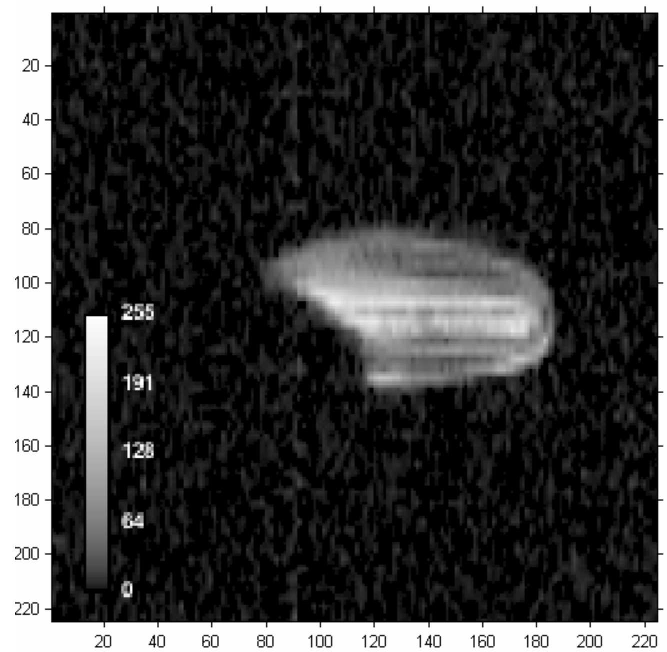


Fig. 7. Subtracted image of an embryo-removed kernel (after 1 h of drying) obtained from Fig. 4(b). The scales show the pixels and the sidebar in the image represents the moisture movement in terms of the grayscale intensity; high gray values represent moisture increase and low gray values represent moisture decrease.

seed coats, and nucellus) high in cellulose, hemicellulose and minerals, which had started functioning as a protective coating with the closely adhered thick-walled cells and started to offer more water resistance. Thus, the MRI images and the gradient vector analyses give a clear indication of the moisture removal pattern that was highly influenced by the grain structural components.

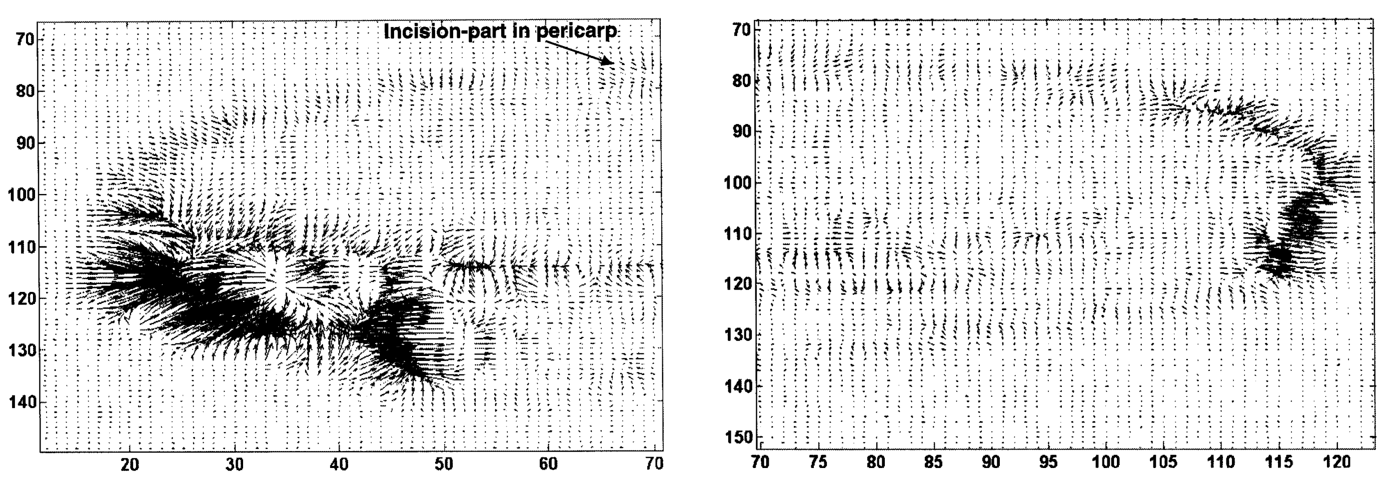
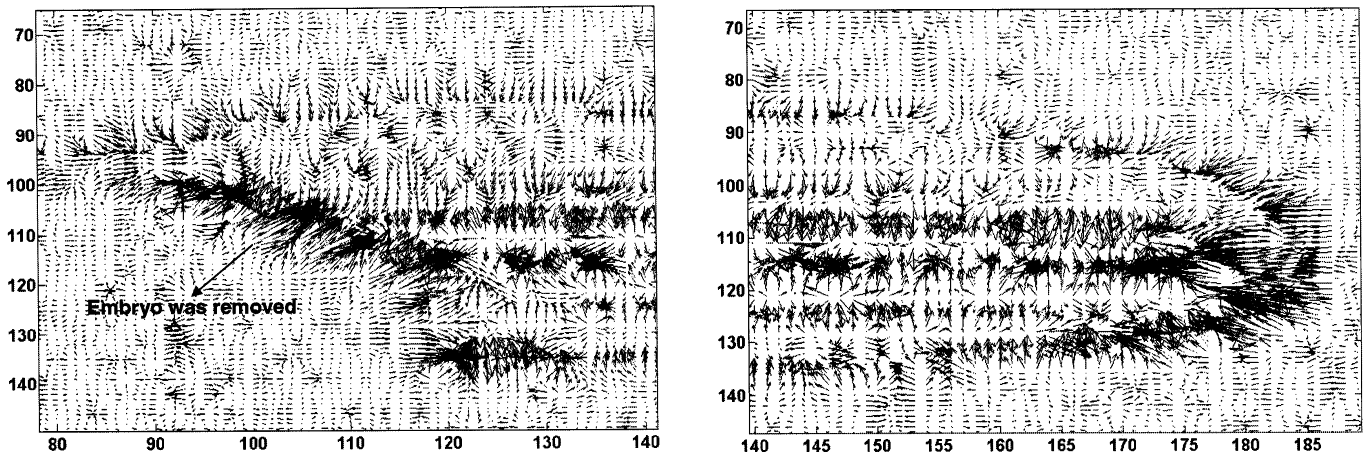


Fig. 6. Gradient vectors of the subtracted image matrix of Fig. 5. (a) shows the embryo and part of endosperm region, and (b) shows the endosperm region.



(a) (b)

Fig. 8. Gradient vectors of the subtracted image matrix of Fig. 7. (a) shows the left portion and (b) shows the right portion.

CONCLUSIONS

The MRI technique was found to be a powerful tool to study moisture movement inside a grain kernel during drying. The MR images showed that the moisture removal pattern during drying of a wheat kernel was non-uniform. Moisture removal also depended upon the grain structural inhomogeneties. Mechanical scarification of the wheat kernel and embryo-removal from the kernel made it easy to visualize the underlying drying phenomena. Moisture appeared to move through the germ end of the wheat kernel from the endosperm after initial stages of drying whereas the pericarp dried faster and presumably acted as an insulator. The germ portion plays an important role in moisture migration during drying. A gradient vector analysis of the MRI intensities provided a mathematical description of the real moisture loss from the kernel during drying. Results of this study will help in mathematical modeling of drying processes and in practical application of the drying theory.

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