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Magnetic Resonance Imaging Studies to Determine the Moisture Removal Patterns in Wheat during Drying

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ABSTRACT

Non-invasive Magnetic Resonance Imaging (MRI) was used to study the drying of single kernels of wheat (cultivar: A.C. Barrie) as a function of time and initial moisture content. Images were obtained using a conventional Spin-Echo pulse sequence on an 11.7 Tesla MR spectrometer equipped with a drying apparatus. Samples of whole kernels (with all three components: pericarp, embryo, and endosperm), mechanically scarified kernels, and embryo-cut kernels were dried at different temperature levels to study the influence of kernel components and drying temperature 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.*

INTRODUCTION

Proper drying conditions are important issues 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 moisture content distribution is uniform in a grain at the beginning of drying and that the moisture removal from the grains 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 benefit of the present method is to understand the underlying mechanism of the grain drying process and to develop 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°C 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 whole kernel during drying. They also found non-uniform distribution of moisture inside the whole 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 whole-wheat kernels. These conditions are an important consideration to develop accurate grain drying models. Further, 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. Therefore, the objectives of this study were to visualize the moisture removal patterns in wheat during drying using MRI and to give a mathematical description of the moisture loss from the whole and mechanically scarified wheat kernel during drying.

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 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 50°C with an accuracy of ±1°C) during the whole drying process while MR images were obtained. Each drying experiments was continued for 4 h. The wheat kernels were preconditioned to a known moisture content (20 to 64% w.b.) by the static equilibrium moisture content method (Solomon 1951) or by imbibition at the beginning of every MR imaging experiment. The initial moisture content of the wheat kernels was determined by the standard air-oven method (ASAE 2003). 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, or cutting the germ end from the kernel.

MRI Data Acquisition

All MR images were obtained using an 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, MB. A Bruker (Milton, ON) Avance DRX console with a ParaVision v.2.1.1 operating system was interfaced to the magnet to record and analyze the images on a SGI

O_2 computer. A conventional three-dimensional multi-slice Hahn spin-echo pulse sequence was used for the MRI data acquisition. Images were recorded as 8-bit, in a 128 x 64 x 8 matrix with a field-of-view of 1.28 x 1.28 x 0.4 cm, resulting in a pixel resolution of 100 µm x 200 µm x 500 µm. 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. Images were processed and analyzed using Marevisi v. 7.1 (Institute for Biodiagnostics, National Research Council Canada, Winnipeg, MB) and Matlab v. 6.5, R13 (The Mathworks, Natick, MA) software.

RESULTS AND DISCUSSIONS

The representative plot of sequential slices (2D) from MRI data sets (3D) collected as a function of time of a whole wheat kernel (approx. 20% w.b.) after every 1 h of drying at 50°C is shown in Fig. 1. Transverse slice number 6 best illustrates moisture distribution in the kernel because this slice has the greatest anatomical detail. The brighter portion represented higher moisture content, and overall signal intensity decreased with time.

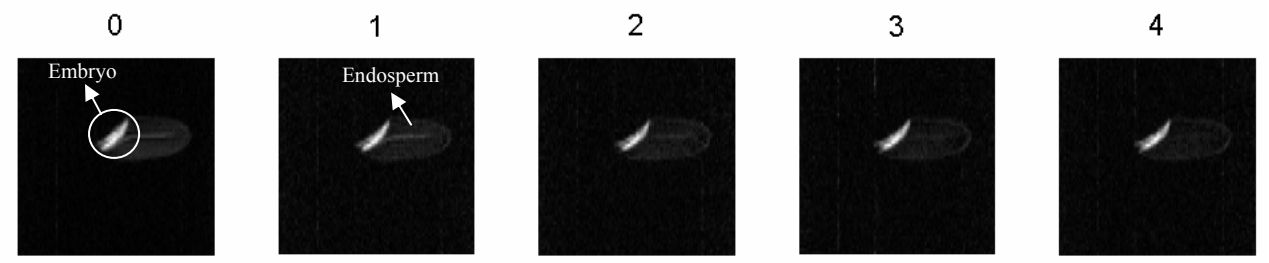


Figure 1 MRI images of a whole wheat kernel during drying at every hour. Drying conditions: temperature, 50°C; drying time, 4 h. Numbers at the top of the images indicate the time, in hours, from the beginning of drying.

Two-dimensional moisture profiles were produced from the 2D MR images (Fig. 2). The moisture movement within the wheat kernel during drying was studied as a function of drying time. The images clearly show a non-uniform pattern of moisture distribution inside the whole wheat kernel during drying. The lowest moisture content occurred in the endosperm. The highest water content was detected in the embryo. The images also revealed that moisture loss was faster from the pericarp and the endosperm compared to the embryo, while the inner part of the embryo remained at high moisture content even after 4 h drying.

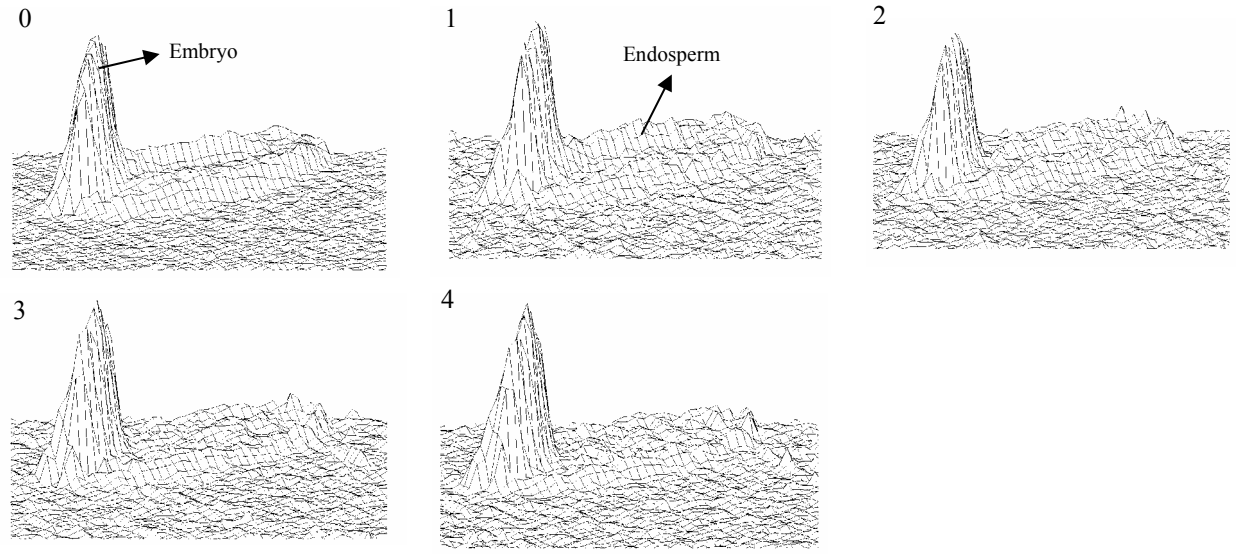


Figure 2 Two-dimensional moisture profiles produced from the top row of Fig. 1.

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:

$$\nabla \mathbf{I} = \frac{\partial \mathbf{I}}{\partial \mathbf{x}} \hat{\mathbf{i}} + \frac{\partial \mathbf{I}}{\partial \mathbf{y}} \hat{\mathbf{j}} \qquad (1)$$

and 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 3 shows the subtracted image of the first (before drying) and second (after 1 h of drying) images of a whole wheat kernel obtained from Fig. 1. The gradient vectors of the moisture loss data for the subtracted image are shown in Fig. 4. The longer the vectors the faster the moisture level decreases. 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 the vectors show outward movement 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 endosperm. This explains why the embryo holds more moisture even after 4 h of drying. Kovács and Neményi (1999) reported a similar effect on moisture removal in corn kernels during drying.

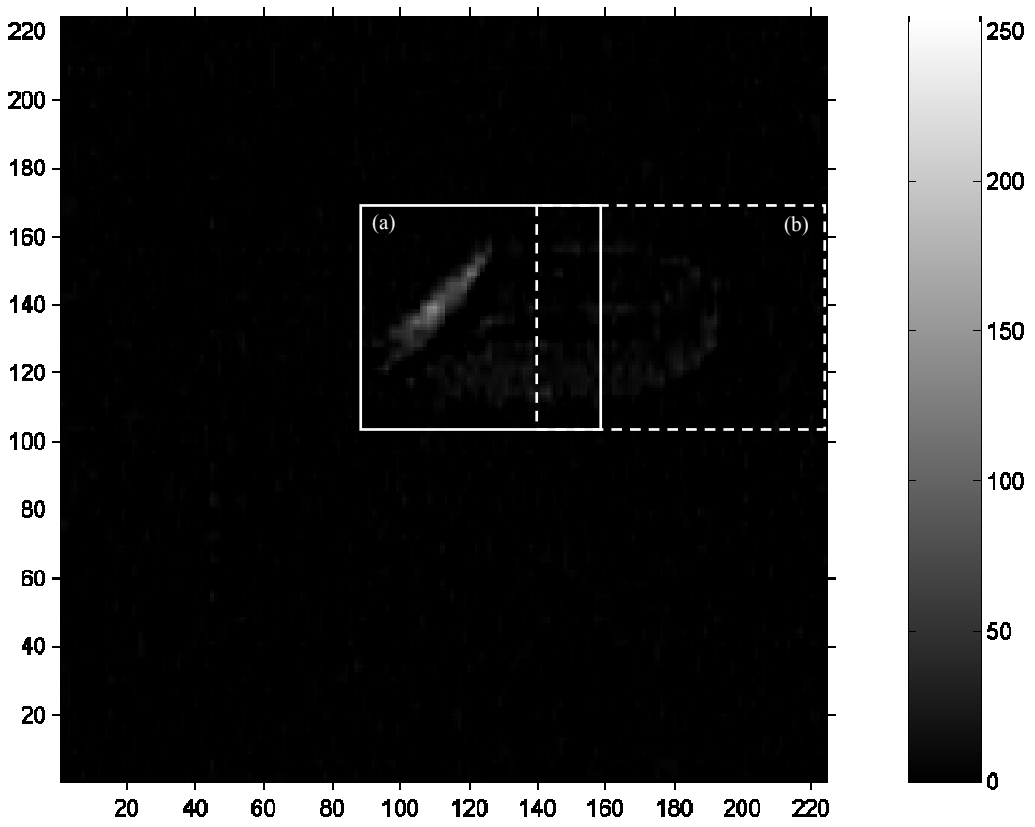
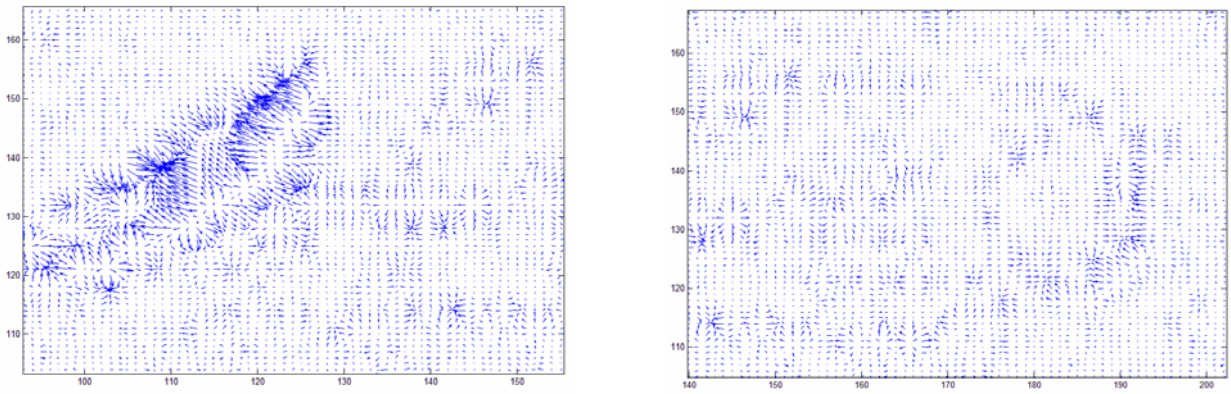


Figure 3 Subtracted image of a whole-wheat kernel (after 1 h of drying) obtained from Fig. 1. The scales show the pixels and the sidebar next to the image represents the moisture movements in terms of the grayscale intensity; high gray values represent moisture increase and low gray values represent moisture decrease. (a) and (b) sections were selected to show the gradient vectors.



(a) (b)

Figure 4 Gradient vectors of the subtracted image matrix of Fig. 3. (a) shows the embryo 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.

For the mechanically scarified kernels (approx. 64% w.b.) and embryo-cut kernels (approx. 37% w.b.), the representative images are shown in Figs. 5a and 5b. The 5th and 6th slices were chosen in Figs. 5a and 5b, 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

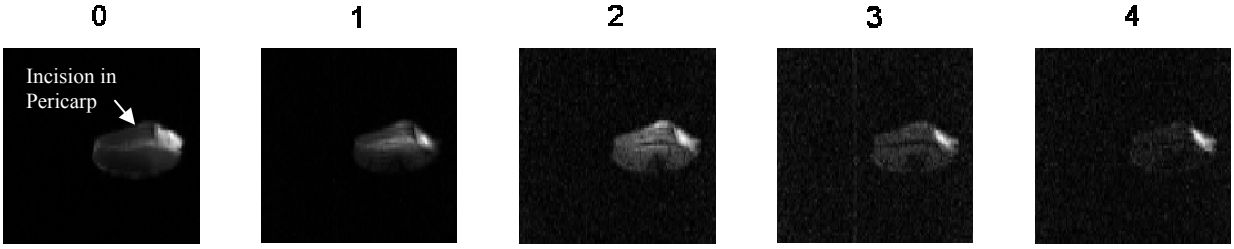


Figure 5(a) MRI images of a mechanically scarified wheat kernel during drying at every hour. Drying conditions: temperature, 40°C; drying time, 4 h. Numbers at the top of the images indicate the time, in hours, from the beginning of drying.

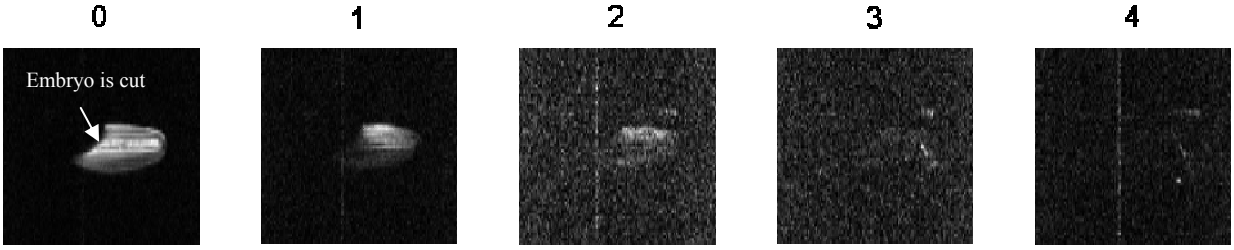


Figure 5(b) MRI images of an embryo-cut wheat kernel during drying at every hour. Drying conditions: temperature, 50°C; drying time, 4 h. Numbers at the top of the images indicate the time, in hours, from the beginning of drying.

test if the site of superficial cutting of pericarp and the removal of embryo influenced the moisture movement in kernels. Figure 6 and 8 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-cut kernel, respectively. Figures 7 and 9 show the gradient vectors of the 2D moisture movement obtained from Figs. 6 and 8 for the mechanically damaged kernels and the embryo-cut kernels, respectively. It can be seen from the Fig. 7 that vectors from the embryo end are directed towards the endosperm section and the length of the arrows is long. Long arrows are also detected at the incision-part of the pericarp region that tend towards outward direction of the kernel. 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.

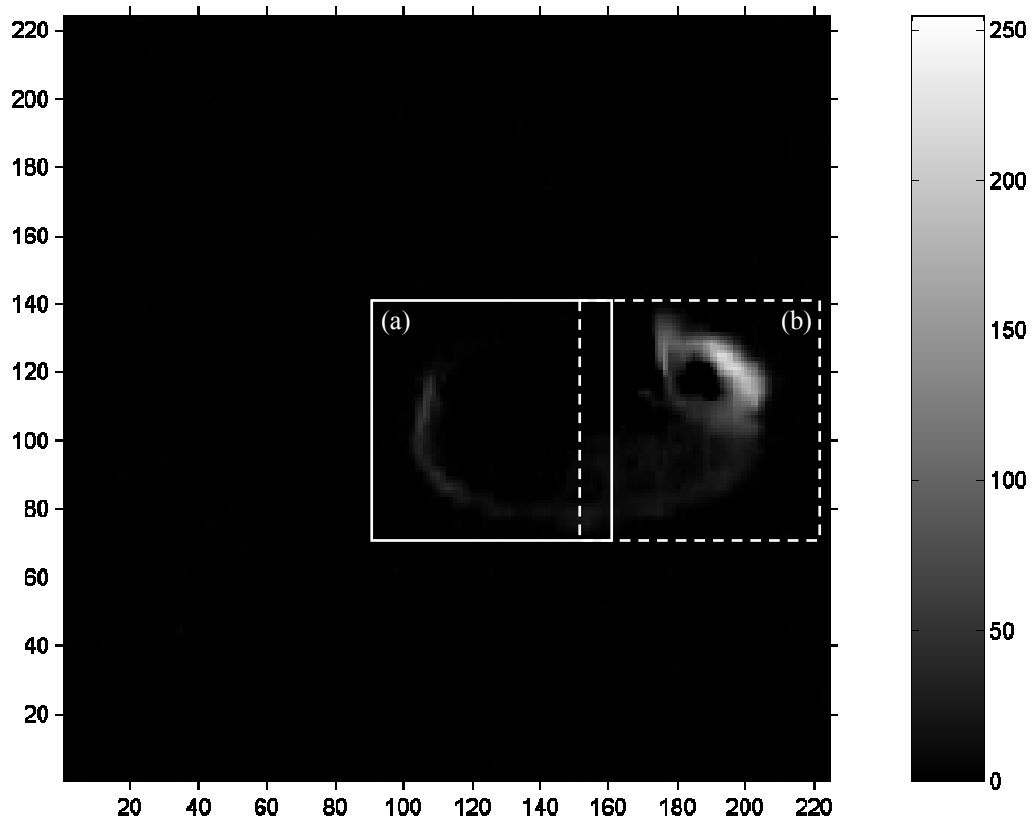


Figure 6 Subtracted image of a mechanically scarified kernel (after 1 h of drying) obtained from Fig. 5(a). The scales show the pixels and the sidebar next to the image represents the moisture movements in terms of the grayscale intensity; high gray values represent moisture increase and low gray values represent moisture decrease. (a) and (b) sections were selected to show the gradient vectors.

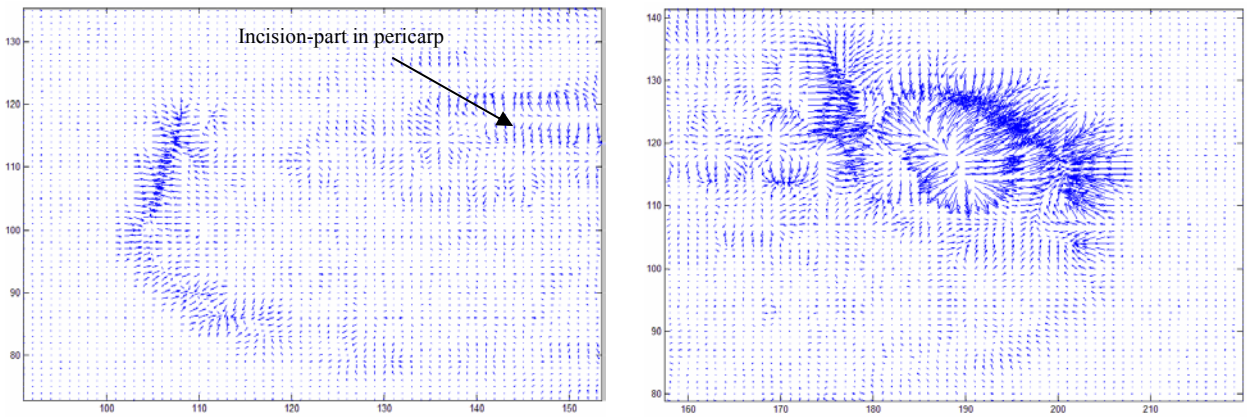


Figure 7 Gradient vectors of the subtracted image matrix of Fig. 6. (a) shows the endosperm region, and (b) shows the embryo region.

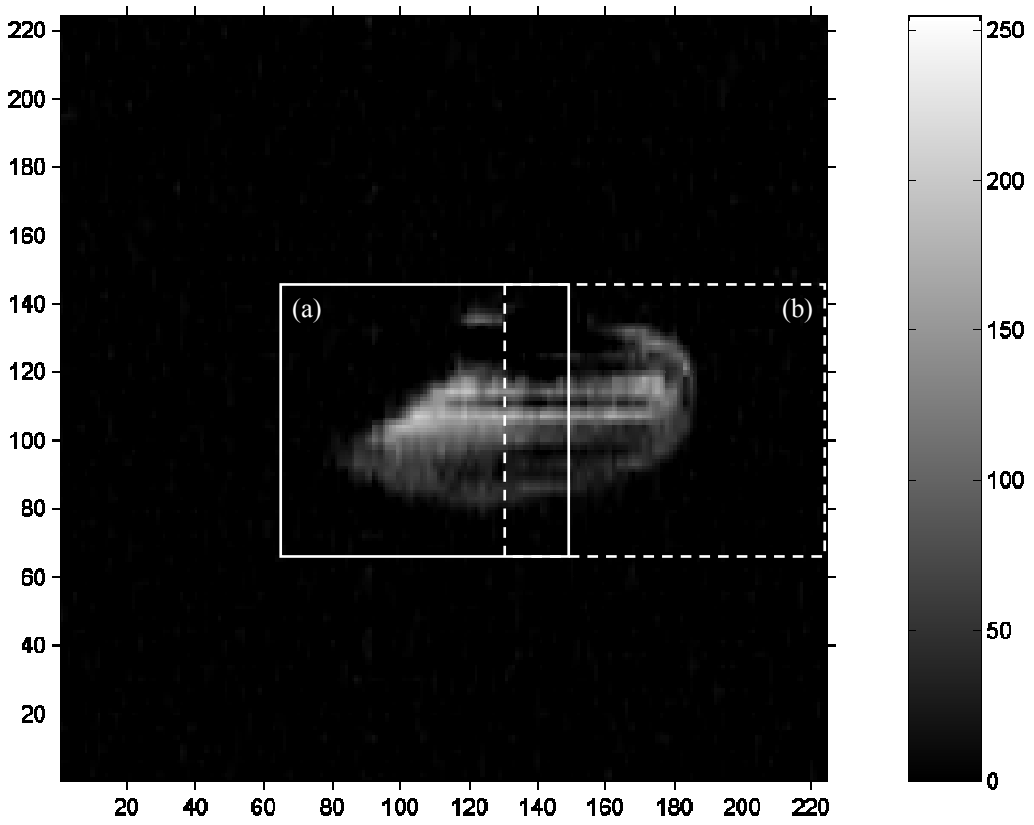


Figure 8 Subtracted image of a embryo-cut kernel (after 1 h of drying) obtained from Fig. 5(b). The scales show the pixels and the sidebar next to the image represents the moisture movements in terms of the grayscale intensity; high gray values represent moisture increase and low gray values represent moisture decrease. (a) and (b) sections were selected to show the gradient vectors.

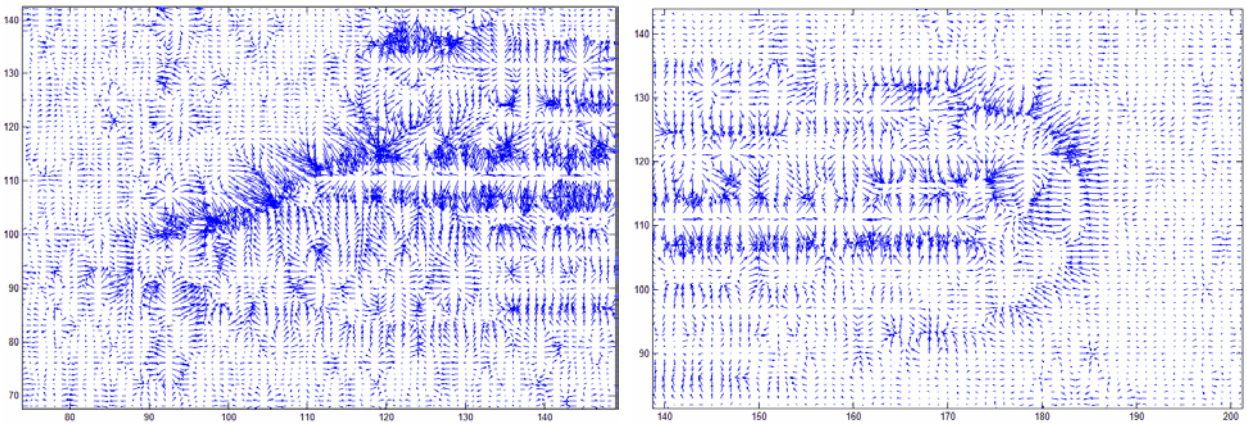


Figure 9 Gradient vectors of the subtracted image matrix of Fig. 8. (a) shows the left portion, and (b) shows the right portion.

However, a damaged pericarp allows moisture to move from the kernel. In the case of embryo-cut 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. 9). 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.

CONCLUSIONS

The MRI images and transient moisture pattern of wheat kernels at different drying conditions with low and high initial kernel moisture content, with whole or mechanically scarified or embryo cut kernels were obtained. The effects of these factors on each component of the wheat kernel during drying was observed by visualizing the images, surface moisture plots, image subtractions, and gradient vector analyses. It was observed that moisture distribution was non-uniform before the start of drying and movement of moisture from the wheat kernels was non-uniform during drying. The results obtained from this study clearly show the potential of MRI as a powerful tool to study the grain drying process.

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