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Application of low-field MRI for quality assessment of 'Conference' pears stored under controlled atmosphere conditions

M. Suchanek[a,*], M. Kordulska[b], Z. Olejniczak[c], H. Figiel[b], K. Turek[b]

[a] Department of Physics, University of Agriculture in Krakow, Al. Mickiewicza 21, 31-120, Kraków, Poland
[b] Faculty Physics and Applied Computer Science, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland
[c] Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, 31-342 Kraków, Poland

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ABSTRACT

A novel, non-destructive, and cost-effective method to evaluate internal disorders occurring in 'Conference' pears stored under controlled atmosphere (CA) is described. A low-field Magnetic Resonance Imaging (MRI) system operating at 0.2 T was used to determine water content in the fruit, and to distinguish damaged and healthy tissues by exploiting the differences of their relaxation times. The extent of damage was evaluated quantitatively by applying a proper segmentation technique to the T_1-weighted images, followed by separate calculation of the volumes of browning tissue and internal voids. The dynamics of the induced changes within the microstructure of the fruit as a function of the CA storage time was analyzed by repeating the measurements periodically during a six-month storage.

1. Introduction

Long-term storage of pear fruit under controlled atmosphere (CA) conditions can lead to internal browning disorders of the flesh, a major cause of postharvest losses. Browning disorders in pears appear as softening and browning of the flesh and the development of internal cavities (Franck et al., 2007). To minimize these effects, it is important to maintain a proper temperature and composition of the storage atmosphere. The storage temperature should be as low as possible to minimize the metabolic activity, at the same time preventing the chilling or freezing damage of the tissue. O_2 and CO_2 partial pressures have to be optimised to slow down the aerobic respiration and thus avoid fermentation (Franck et al., 2007). The application of inappropriate storage atmosphere conditions can result in a serious deterioration of the fruit tissue without any visible external symptoms. Therefore, there is a strong demand for a non-invasive method that would detect the internal browning and its development during the CA storage, keeping the fruit intact. The method should be reliable, cost-effective, and feasible for commercial applications for harvested fruit.

Magnetic Resonance Imaging (MRI) has found many applications in food processing and analysis (Opara and Pathare, 2014; Patel et al., 2015; Sozer, 2016). It is a quantitative and non-destructive method to determine the internal defects or diseases of a specimen, and to visualize structural changes that occur during processing. Using the magnetic properties of hydrogen nuclei and their interaction with external magnetic fields, three-dimensional images of water density and its mobility in biological systems can be obtained. Any alteration in the chemical composition of fruit flesh, its disintegration, or the occurrence of internal voids can affect the dynamics of water that is present inside the tissue. This in turn modifies the relaxation times of protons in water, which can be used as contrast parameters in the MR images enabling to observe even small changes of the fruit flesh composition, not visible with other methods.

MRI methods have been used to investigate the occurrence and development of internal disorders in fruit and vegetables, for example, in apple (McCarthy et al., 1995; Melado-Herreros et al., 2013; Wang et al., 1988), kiwi fruit (Taglienti et al., 2009), strawberry (Otero and Prestamo, 2009), mango (Joyce et al., 2002), tomatoes (Milczarek et al., 2009, Musse et al., 2009), cucumbers (Kotwaliwale et al., 2012) and potatoes (Thybo et al., 2004).

Wang and Wang (1989) found that MRI is suitable for a non-destructive detection of the core breakdown in the 'Bartlett' pears, but few subsequent studies of the MRI application for the quality assessment of pears are available. Lammertyn et al. (2003a) measured the spatial distribution of the core breakdown symptoms in 'Conference' pears by MRI and X-ray computer

* Corresponding author.
E-mail address: m.suchanek@ur.krakow.pl (M. Suchanek).

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tomography (CT) techniques. Both methods were found to be well suited to detect the browning tissue and cavities in affected pears, but MRI was more sensitive, especially in the case of incipient brown discoloration. Lammertyn et al. (2003b) studied the development of core breakdown and cavity formation over time during storage of the same species. They showed that when the flesh browning occurs, it does not expand during storage, but the MRI contrast between the affected and healthy tissues is enhanced due to the changes of T_1 relaxation time, indicating much more severe damage. The disorder area does not increase in size but the affected tissue gradually dries out and cavities are formed in and nearby the core. Nguyen et al. (2006) used high field MRI to validate a model of macroscopic water transport in pears during storage, adopting a finite element approach based on the Fick's second law of diffusion. Hernández-Sánchez et al. (2007) developed a non-destructive procedure for on-line browning disorder identification in pears by MRI. The healthy and damaged pears were differentiated using the T_2^* relaxation time – and proton density – weighted images that were acquired with the fast FLASH MRI sequence. Zhou and Li (2007), Zhou et al. (2008) used the T_2-weighted MR images to perform texture analysis of stored pears without and with protective coating, respectively. Examples of high-field 3D MR microimages of various fruit, including pears, were shown by Moriwaki et al. (2014). The imaging of relatively hard vascular structure was achieved by using the T_1 contrast, which enhances the signal from motionaly restricted protons.

Most MRI studies of browning disorders in pears described above were carried out using either 4.7 T research or 1.5 T medical systems that are based on expensive superconducting magnets. The only exception is the pioneering study of Wang and Wang (1989), who used the 0.5 T medical MRI system. The major advantage of high-field MRI is high signal to noise ratio (SNR), which improves spatial or/and temporal resolution, or equivalently, reduces the acquisition time while preserving the image quality. However, the high cost of the MR equipment and the difficulty in placing a superconducting magnet in a food processing environment, makes this technique unfeasible for the routine inspection of fruit and vegetables. Low-field systems based on permanent magnets could be a reasonable alternative, because inherently lower quality of images may be still sufficient for the evaluation of individual fruit. Haishi et al. (2011) successfully studied the larval activity in growing and post-harvest apples using the 0.2-T MRI system with the dedicated solenoid transmitting coil and surface receiving coil to shorten the measurement time. Geya et al. (2013) imaged the growing pear fruit using a dedicated mobile MRI system at the same magnetic field strength. Some attempts were also undertaken to apply the low-field MRI technique directly to fruit on a moving conveyor belt (Chayaprasert and Stroshine, 2005). However, motional artifacts lead to the fruit misclassification, so significant reduction of the measuring time would be necessary for successful implementation of this method.

Herein, we report on the application of dedicated 0.2 T MRI system to monitor the browning process in 'Conference' pears that occurs during storage under CA conditions. In spite of low field, it was possible to detect incipient physiological changes in the fruit. The browning and disintegration of the fruit tissue was clearly identified on the T_1-weighted MR images obtained by the multislice spin echo (MSE) sequence. This imaging technique was found to be the best at low field for imaging lesions in the flesh tissue associated with moisture loss. Based on the MR images, the expansion of disordered tissue and the time development of internal cavities was evaluated.

In general, the differences in several physical parameters can be exploited to enhance the contrast of the MR images of biological tissues: T_1, T_2 relaxation times, proton density (PD), susceptibility effects, and chemical shift. The last two are irrelevant in low-field MRI, and PD does not provide sufficient contrast, because water densities in healthy and damaged tissues are not very different. The relaxation of nuclear spins is governed by the time-dependent part of the dipolar Hamiltonian, which is modulated by translational and rotational motion of water molecules. This leads to finite transition probabilities between Zeeman energy levels of nuclear spins. In principle, in the so called motionally narrowed limit, the higher mobility of water molecules, which means shorter correlation time, leads to longer relaxation. Therefore, in T_1-weighted images, regions with high content of free water can be distinguished from the regions containing bound water, appearing dark and bright in the image, respectively. This produces a positive contrast for the damaged tissue, in contrary to negative contrast that would be observed in the T_2-weighted images.This is advantageous when a segmentation procedure has to be performed in low Signal-to Noise images, which are typical in the low-field MRI. Moreover, the acquisition time for the T_1-weighted images is much shorter.

There are possible distortions in the MRI images, resulting from air-tissue interfaces that are present in biological tissues. They are caused by local magnetic field inhomogeneities due to different magnetic susceptibilities of air and the tissue and may reduce the accuracy of the method. In our case a partial dehydration of the damaged regions of the pear occurs and the amount of air increases. Therefore the Spin-Echo (SE) imaging sequence was chosen, in which the signal loses due to susceptibility effects are lower than in the Gradient-Echo (GE) sequence.These effects strongly depend on the magnitude of static magnetic field, therefore the application of low-field technique is advantageous (Musse et al., 2010).

2. Materials and methods

2.1. Fruit material

Pears of 'Conference' cultivar (15 kg) were bought on November 20th 2014 in the Experimental Station of Department of Pomology and Apiculture of the Agricultural University in Krakow soon after harvesting. All pears were weighted on a digital balance, sorted for weight and the seven largest fruit were chosen with an average mass equal to 213 ± 16 g. Selected fruit were labelled and put into a digital laboratory incubator (ILW 240 STD, Pol-Eko Aparatura) with an air circulation system stabilizing the temperature to within $\pm 0.4\,^{\circ}$C. The glass exsiccators located inside the incubator produced the required CA conditions. The fruit were stored under browning inducing condition with the following atmospheric parameters: $O_2 < 1\%$, $CO_2 > 1\%$, $10\,^{\circ}$C, in the time period from November 20, 2014 to May 12, 2015. The internal browning developed in four fruit out of seven that were stored, and the changes were rather large in two of them.

Six MRI measurements were performed during the storage period on the following dates: December 1 2014 and January 19, February 9, March 3, March 31 and May 12, 2015. The first MRI experiments were performed soon after placing the fruit in CA, whereas the last one was chosen when the changes in the fruit had reached their maximum. The controlled temperature and gas composition were not maintained during the 5 h period that was required each time for the fruit transport to the MRI apparatus and data acquisition.

2.2. Magnetic resonance imaging

Proton (^{1}H) MRI experiments were carried out on a 0.2 T low field MRI system (Cirrus Open, MRI-TECH, Poland), equipped with an open-frame, temperature stabilized, permanent magnet with a spherical homogeneous operating volume of 30 cm diameter.