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자기공명영상을 이용한 농축산물의 비파괴 내부품질 평가

Nondestructive Internal Quality Evaluation of Agricultural Products using Magnetic Resonance Imaging

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적 요

자기공명영상 (MRI) 기법은 최근에 그의 이용 분야가 식품공학 및 농학 분야까지 확대되고 있다. 이 연구에서는 MRI의 기본 원리를 알아보고 어떤 요인들이 자기공명영상의 명암을 결정하는지 알아 보았다. MRI를 이용하여 비파괴적인 방법으로 농축산물의 내부 구조 영상을 얻고 이로부터 토마토의 내부 공동, 감자의 공동병, 사과와 파파야의 멍, 버찌씨의 유무, 망고와 감자의 벌레에 의한 손상, 망고와 마늘의 내부 결함, 키위의 성숙도에 따른 변화, 그리고 소고기의 내부 구조 등을 판별할 수 있음을 알아 보았으며 농축산물의 품질을 결정짓는 이러한 내부 요인들이 어떻게 자기공명영상을 형성하는지 알아 보았다. 대상 시료에 따라 적당한 자기공명영상 인자(TR과 TE)를 선택하여야 한다. 또한 특정 인자를 강조하기 위해서는 최적의 자기공명영상 인자를 선택하여야 한다.

주요용어(Key Words): 자기공명영상(Magnetic Resonance Imaging, MRI), 비파괴적 평가(Nondestructive Evaluation), 농축산물(Agricultural Products), 내부품질(Internal Quality)

1. Introduction

Quality evaluation of agricultural products has been an important process for grading, processing, sorting, and marketing. Need for better quality products has increased research and development related to quality evaluation measurements and techniques. Most fruits and vegetables are not harvested at the same stage of maturity due to biological and environmental differences. While modern mechanical harvesting for the products being processed reduces production cost, it also increases the need for proper sorting of the products. Even hand-picked products for fresh market could benefit from the additional quality sorting.

Automated sorting machines can grade fruits into several categories according to specified quality evaluation rules. The quality evaluation rules can roughly be divided into two parts: external and internal. Size, shape, surface color, defects and bruises can be categorized as external quality factors and internal

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voids, solids, disorder, and composition can be categorized as internal quality factors.

Detecting external quality factors is relatively easier than detecting internal factors by nondestructive methods. Light reflection and image processing systems are commercially used for external quality evaluation instead of manual sorting. Many internal quality attributes are hard to be detected by nondestructive methods. Researchers have been working to find methods for evaluating internal quality attributes of agricultural and food products nondestructively by measuring their physical, acoustical, electrical, optical, X-ray, and nuclear magnetic resonance (NMR) properties (Gunasekaran et al., 1985; Dull, 1986; Chen and Sun, 1991; Self et al., 1993, ASAE, 1994). Most of these techniques detect certain physical properties of the material, and hence, are suitable only for evaluating specific quality factors. Moreover, some techniques have potential radiation hazards caused by X-ray and gamma ray radiation. Sonic and optical methods have limited penetration depth on certain biological tissues (Chen et al., 1989).

The areas of nondestructive internal quality evaluation can be divided into detection of internal structural features and detection of chemical composition. Internal structural features include interior voids, foreign material, insects, internal solids such as pits or stones, and internal disorder. Chemical compositions include water, sugar, and oil.

Most nondestructive internal structural feature detection techniques are based on the principles of buoyant force, light interaction, X-ray, microwave, ultrasound, and NMR (ASAE, 1994). Researchers have investigated defect detection techniques using buoyant force, light interaction, and X-ray earlier than those using microwave, ultrasound, and NMR. Detection of internal structural features requires an imaging capability in most cases. Due to advances of modern computer technology and hardware cost reduction, researchers can utilize X-ray and NMR systems which have imaging capability and are widely used in medical radiology. Therefore, to examine the applications of X-ray and NMR imaging methods and to compare their utilization are important research areas.

In the applications of X-ray systems, Lenker and Adrian (1971) used an X-ray system to determine the maturity of lettuce heads and Diener et al. (1970) applied this technique for detecting bruises in apples. Hollow heart in potatoes was investigated by Finney and Norris (1978). X-ray systems are commercially used for detecting hollow heart in potatoes (Rex and Mazza, 1989). Brecht et al. (1991) showed X-ray computed tomography images indicating the difference between mature and immature tomatoes and suggested this method could be used for a nondestructive maturity evaluation. Thomas et al. (1993) used an X-ray imaging system to detect an internal disorder called spongy tissue in mango fruits and demonstrated the high potential of an automated X-ray system for sorting mangoes. In the citrus industry, commercial X-ray systems were installed and successfully used in detecting seeds and internal voids (Johnson, 1985).

Even though applications of magnetic resonance imaging (MRI) to agricultural products doesn't have a long research history like X-ray, many researchers have investigated this technique recently due to its potential in quality evaluation. Hinshaw et al. (1979) demonstrated the accurate measurement of the internal structure of intact fruits that could be restored accurately using MRI methods. Wang et al. (1988) used MRI to study watercores and their distributions in Red Delicious apples from MR images. The difference between the normal and watercored tissues was clearly separated by intensity differences on the MR images. Chen et al. (1989) showed MRI was very effective in detecting most internal quality factors such as bruises, dry region, worm damage, stage of maturity, presence of voids, seeds, and pits of agricultural products. Ishida et al. (1989) investigated physiological changes during maturation of a tomato using MRI and Williamson et al. (1992) used microscopic MRI of red raspberry with voxel (volume element) dimensions of $70 \times 70 \times 50$ μm to study the changes in spatial distribution of mobile protons. Clark and Forbes (1994) and Suzuki et al. (1994) studied thermal injuries of persimmon and papaya caused by chilling or heating using a MRI based method. McCarthy et al. (1995) detected bruises in 2-D MR images of apples and analyzed the sources of image contrast caused by bruises. Most of former works were done from a biological point of view rather than an engineering point of view. Zion et al. (1993) detected pits in cherries from MRI 1-D profiles and demonstrated a potential for using this method as the basis of a high speed on-line sorting system.

The objective of this study is to demonstrate the feasibility of detecting various quality factors in fruits and vegetables using an MRI technique as an internal structural feature acquiring tool.

2. Materials and Methods

A 2T super conducting magnet (General Electric CSI-2) operating at a proton resonant frequency of 85.5 MHz was used for this study. A home made 10 cm diameter birdcage coil or a 15 cm diameter commercial imaging coil from General Electric was used to acquire the image data. Images were taken using spin echo pulse sequences. Echo times (TEs) varied from 15 ms to 100ms and repetition times (TRs) varied from 100 ms to 800ms. Slice thickness was 10 mm and image size was 128×128 pixels. Images were inverted in this study so that strong signals showed darker gray level and weak signals showed whiter gray level for display purpose (originally strong signals appeared as dark regions and weak signals and background noises appear as white regions in magnetic resonance images). Samples were purchased at a local market or donated from fruit researchers. An image processing and analysis software was programmed to analyze the spin-echo images using MATLAB for Windows (version 5.0, MathWorks Inc., Natick, Mass.).

Principles of MRI

MRI is a collection of experimental techniques that are designed to allow one to measure the NMR properties of a sample as a function of spatial position. The basics of MRI will be explained based on the spin-warp imaging technique. The experiment proceeds by placing the sample in a homogeneous external magnetic field. Pulsed linear magnetic field gradients are used to produce frequency variations across the sample that can be converted into spatial coordinates. The relationship between frequency and magnetic field is:

$$\omega = \gamma (B + Gx)$$

where ω is the Larmor frequency (rad/sec), γ is gyromagnetic ratio, B is the main external magnetic field in Gauss (usually in Tesla), G is the linear magnetic field gradient (in Gauss/cm) and x is the spatial distance (cm). For instance, if a linear gradient G is applied in the x direction then the precessional frequency becomes a function of the sum of the homogeneous field and the linear gradient. The frequency spectrum can easily be converted into a position-dependent signal intensity. By the proper application of gradient one-, two- or three-dimensional mappings of the NMR signal intensity can be recorded (McCarthy, 1994).

Contrast in NMR Images

In MRI, spin-echo is an important MR

phenomenon and used to acquire an MR image. The amplitude of the MR signal that is proportional to the concentration of mobile protons at a certain point in a sample causes the intensity or brightness at that position in a magnetic resonance image. Mobile proton density, and relaxation times T_1 and T_2, which are sample-dependent parameters are good sources for generating contrast in an MR image. There are two important experimental parameters used to acquire an MR image. These are TR which is the time interval from the beginning of a pulse sequence until the beginning of the next pulse sequence, and TE which is time gap from the first radio frequency (RF) pulse of a pulse sequence to the middle of a spin echo (Callaghan, 1991). These parameters can be varied to provide the contrast that describes the structure of a sample.

Additional factors affecting the contrast of an MRI image are chemical exchange of molecules, inhomogeneity of local magnetic field due to variations in the diamagnetic susceptibility within the sample (for example, intercellular liquids and intracellular air pockets have different susceptibility), and motion of spins through spatial variations in the magnetic field.

3. Results and Discussion

Internal structural features of agricultural products such as interior voids, bruise, insect damage, pit detection, internal disorder, and maturity were determined using MRI techniques. The techniques were applied for analyzing internal structures of beef nondestructively. Effects of MRI parameters such as TR and TE were discussed. It takes about two minutes to acquire a 2-dimensinal image with the MRI system used in this experiments. Therefore, current experimental set-up is not suitable for on-line use using 2-dimentional images.

Interior voids

Interior voids caused by insects, physiological phenomena, etc. generate weaker signals (whiter gary level in this study) than normal parts of fruits in MR images. Fig. 1(a) shows an air pocket inside of an immature tomato, and fig. 1(b) shows a hollow heart defect of a potato. In an early stage of maturity of tomatoes locular area did not develop well. Therefore, there is an air pocket.

Bruise

MRI techniques could determine external and internal bruises. Fig. 2(a) shows 48-hour bruise of an apple and fig. 2(b) shows old bruises of an apple. Bruise damage caused by external forces happened in 48-hour results in tissue cell destruction and rearrangement of mobile water. Therefore, the damaged region generates strong signals. The old bruises were very old bruises that had already dehydrated by a visual inspection of the cut fruit. Fig. 8 (a) shows internal bruise that happened within one week of a papaya.

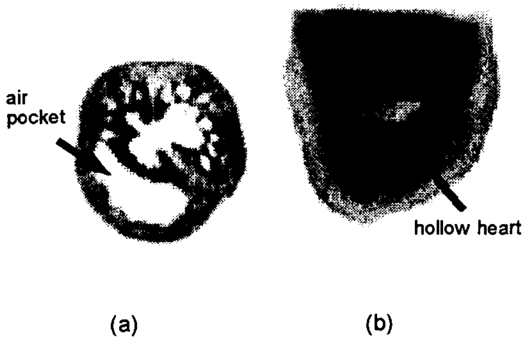
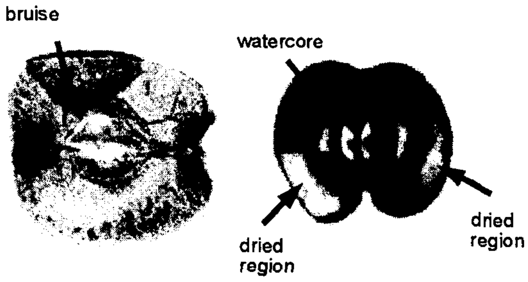
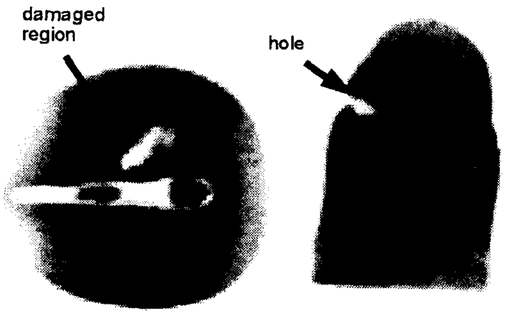


Fig 1. Various types of internal voids of fruits. (a) air pocket of an immature tomato. (b) hollow heart of a potato. MRI parameters: (a) TR=200ms and TE=60ms. (b) TR=500ms and TE=15ms.



(a) (b)

Fig. 2 Images of apples with 48-hour bruise (arrow) (a), and dried region (two lower arrows) and water core (upper arrow) (b). MRI parameters: (a) TR = 100ms and TE = 30ms. (b) TR = 500ms and TE = 15ms.

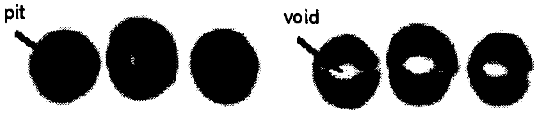


(a) (b)

Fig. 3 Images of damaged mango by a weevil (a) and a hole (arrow) in a potato caused by a wire worm (b) MRI parameters: (a) TR = 800ms and TE = 15ms. (b) TR = 500ms and TE = 15ms.

Insect damage

Holes or voids caused by insects generates weaker signals in MRI. Fig. 3(a) shows an image of a weevil damaged Hawaiian mango and fig. 3(b) shows a hole in a potato caused by a wire worm. MRI could be used to sort out internally damaged fruits.



(a) (b)

Fig. 4 Images of unpitted (a) and pitted (b) cherries. MRI parameters: TR = 100ms and TE = 30ms.

Pit detection

An inside seed which contains water and oil of a pit of a fruit generates strong signals. However, a hard shell of a pit contains very few water so it generates weak signals. From unpitted Bing cherry images shown in fig. 4(a), flesh and inside seed parts appear as a darker gray level than the shell part. After pitting process void spaces in the center of cherries are bright, which means no signals are generated from those parts. MRI can be used to detect seeds or pits inside fruits.

Internal disorder

Internal disorders such as tissue breakdown, rot, water core, etc. are caused by physiological and anatomical changes of fruits. Dried region caused by a bruising shows up as a white areas in fig. 2(b) and internal void caused by a tissue breakdown of a mango generates no signal like shown in fig. 5(a). Whereas rotten areas of garlic shown in fig. 5(b) and water core of an apple shown in fig. 2(b) generate strong signals, which means there are a lot of free water and great metabolic activities.

(a) (b)

Fig. 5 Images of internal tissue breakdown (arrows) of a mango (a) and a rotten garlic (arrow) (b). MRI parameters: (a) TR=100ms and TE=30ms. (b) TR=500ms and TE=16ms

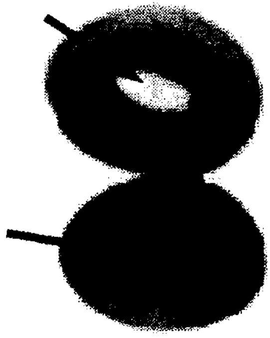
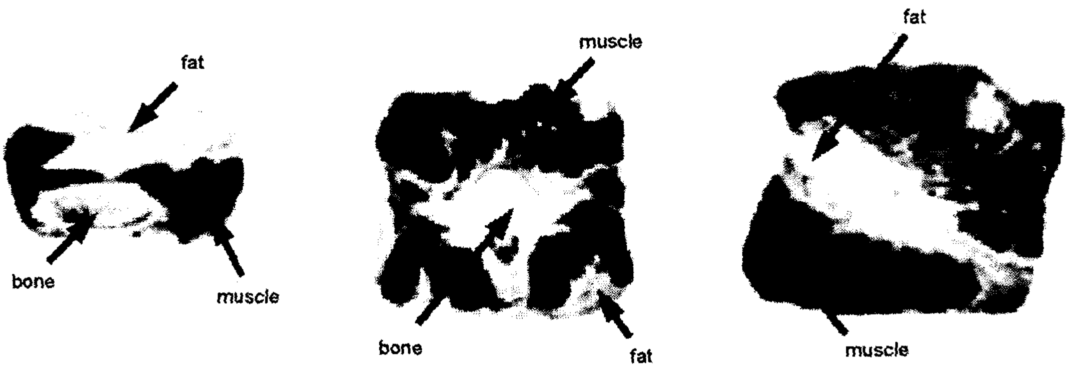


Fig. 6 Image of immature (top one) and mature (bottom one) kiwis. MRI parameters: TR=250ms and TE=50ms



(a) (b) (c)

Fig. 7 Images of beef, rib (a), ox tail (b) and top round (c). In these images lean meat generates stronger signals than fat and bone parts. MRI parameters: TR=700ms and TE=15ms.

Maturity

As fruits mature they have more water and oil, which can be detected by the MR techniques. Fig. 6 shows two kinds of kiwi fruits, one is immature and the other is mature. There are three clear layers regardless of their degree of maturity. However, the center part (refer arrows) of an immature kiwi fruit generates less signals than that of a mature one. This indicates that MRI can be used for determining kiwi maturity.

Beef quality

MRI technique was used to investigate the internal structure of three kinds of meat samples: rib, top round and ox tail (refer fig. 7), and it was very successful. The inner parts (muscle, fat and bone) of the three samples were clearly seen on the images and it is possible to distinguish the structure by naked eyes and evaluate the quality factors such as marbling, vague amount of fat and muscle. That means this method can be used for quality evaluation in terms of eye investigation.

Effects of MRI parameters on the MR images

In addition to physical properties of fruits and vegetables magnetic resonance imaging parameters such as TR and TE affect on the contrast of MR images. Fig. 8 shows magnetic resonance images of a papaya. These two images were acquired with TR= 100ms and TE=30ms (a) and TR=200ms and TE= 20ms to show the combined effects of the imaging parameters. Without changing any experimental setups to enhance the structural feature the imaging parameters were changed to enhance an internal bruise of a papaya. In some cases optimal imaging parameters are needed to get specific features.

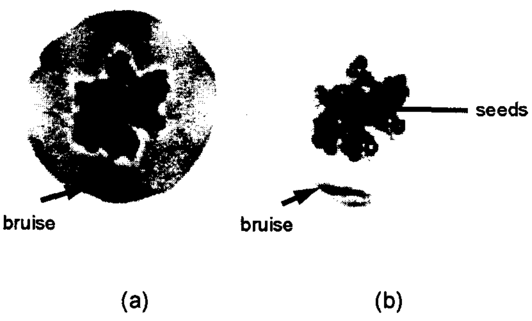


Fig. 8 Images of a papaya with different MRI parameters: (a) TR=100ms and TE=30ms. (b) TR=200ms and TE=20ms.

4. Conclusions

Many researchers have investigated magnetic resonance techniques recently due to its potential in quality evaluation. Magnetic resonance imaging demonstrated the feasibility of detecting various internal quality factors nondestructively. Interior void of a tomato, hollow heart a potato, bruises of apples and a papaya, insect damages of a mango and a potato, pits of cherries, internal disorders of a mango and a garlic, maturity of kiwi fruits, and beef quality could be seen clearly from magnetic resonance images of the agricultural products. Different magnetic resonance imaging parameters such as TR and TE were needed to get structural features of various fruits and vegetables. To enhance specific features on the magnetic resonance images optimal imaging parameters were needed.

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