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A Simple Overview in Magnetic Resonance Imaging Application in Evaluation of Food Quantity and Quality Aspects

Toktam Mohammadi-Moghaddam[1,2], Mohammad Morshedi[3], Afsaneh Morshedi[4*] and Marcos Eduardo Valdes[4]

[1] *Workplace Health Research Center, Neyshabur University of Medical Sciences, Neyshabur, Iran*
[2] *Department of Food Science and Technology, Neyshabur University of Medical Sciences, Neyshabur, Iran*
[3] *Department of Geophysics, Tehran University, Tehran, Iran*
[4] *Facultad de Ciencias Gastronómicas y Turismo, Universidad UTE, Quito, Ecuador*

[*] Correspondence to:
Afsaneh Morshedi
Facultad de Ciencias Gastronómicas y Turismo,
Universidad UTE,
Quito, Ecuador.
E-mail: Afsaneh.morshedi@ute.edu.ec

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Abstract

Magnetic resonance imaging (MRI) has been a professional method in medical diagnostics for many years. Recently, considering the increase in population, preparing healthy food is a worldwide challenge. Hypothesis and implementation of MRI in research of food is approximately new. MRI is considered as a green, noninvasive, low cost, rapid, and nondestructive experimental method for investigating food processing. This method could be used in a short time while its results are suitable to apply in different industries even in online monitoring. Utilizing MRI techniques enhances the capacity to quantify basic processes such as gelation, crystallization, drying, dehydration, freezing, diffusion, and flow that occur in food products. This technology equips food scientists with a robust tool in the physicochemical properties study of food systems or specified food components and assessing them throughout diverse processes. This technique has some disadvantages in some process conditions too.

Keywords

Magnetic resonance imaging, Magnetization of materials, Image, Green method, Nondestructive analysis

Introduction

The increased demand for food is a significant challenge for global food security and some of the foods are more important because are categorized as staple foods [1]. Usually, politics about solving this problem is focused on improving grains like wheat using classic and molecular breeding techniques [1, 2], and enhancing the quality and durability of some food products. Usually, food is a combination of grains, fruits, vegetables, meats, and additives. Quality control of these complicated mixtures is difficult and needs a lot of time [3, 4].

Application of MRI technology holds immense potential in the food industry, during a short time [4, 5]. MRI usage could be qualitative and quantitative, but in different eras. Its usage in medical science is qualitative, contrary to its use in the food industry [6]. Food quantity usually has two aspects: physical properties (volume, surface, area, and porosity), and chemical properties (moisture content, oil content, and other basic compounds) [6-8].

MRI enables non-destructive and detailed analysis of food quality, composition, and safety parameters as well [9, 10]. By generating high-resolution images, MRI can detect internal defects, monitor moisture content, and assess structural integrity without altering the food's properties, even in opaque systems [3, 10-12]. This capability is invaluable for ensuring the safety and quality of food products throughout production, storage, and distribution processes [13]. As technology advances, MRI continues to play a pivotal role in enhancing food safety standards and ensuring consumer confidence in the global food supply chain [3, 14].

In a world dominated by MRI, which utilizes proton resonance, this non-invasive imaging technique holds sway primarily in medical diagnostics [15, 16]. Recently, MRI technology has expanded beyond traditional boundaries, penetrating various fields such as the intriguing realm of food science and technology [11, 12, 17, 18]. It now plays a pivotal role in exploring food systems, providing valuable insights into the physical and chemical properties of edibles, while ensuring the integrity of the sample [19]. The captivating ability of MRI to reveal detailed insights into the internal structure, composition, and dynamics of materials has sparked enthusiastic interest among scholars and industry experts, driving them towards new realms of innovation in food quality assessment, process optimization, and product development [8, 15, 20-24].

Samples can undergo multiple studies under consistent or modified conditions, providing notable benefits such as time efficiency, heightened accuracy, and more detailed interior surface analysis compared to preparative microscopy. In many cases, food systems require meticulous step-by-step construction from fundamental ingredients to complex systems to investigate the impacts of individual components and assess interactions between them. By comprehending the underlying processes deeply, it becomes economically viable to develop novel products or equipment with improved processing conditions during production [20, 25-29]. The limitation of using MRI is in the process that some part of food changes his physical property. For example, during drying, freezing, chilling, and freeze-drying process, monitoring by MRI has faced with challenge and because of phase changing in fats and water, the final data may be not exactly reliable [10, 12, 30].

Techniques of MRI expand our ability to measure fundamental processes taking place within food products, such as crystallization, dehydration, gelation, diffusion, and flow [31]. MRI enables non-disturbing measurements of mobility, saturation, and chemical species compositions. This includes studying phenomena like fat crystallization, emulsion stability, fruit maturation, freezing processes, fat content, and volumetric changes [32-35]. Recently, many researchers have studied process controlling with MRI in different fields: meat science, cereal science, fishing industry, fruits and vegetables storage, dairy industry [36-43].

Hypothesis of MRI

Basic principles of MRI

MRI methods utilize the magnetic properties of a material's protons, which arise from the interaction between the atomic particles of the material and a magnetic field that exist externally (Figure 1 and figure 2). Every proton possesses a magnetic moment, while are aligned in the same direction or in the opposite direction with the external magnetic field [44].

When protons are aligned in the same direction, they need lower free energy comparing opposite direction. Proton numbers that are aligned in the same direction (B_0) are slightly higher than the ones that face the opposite direction (Figure 3) [44].

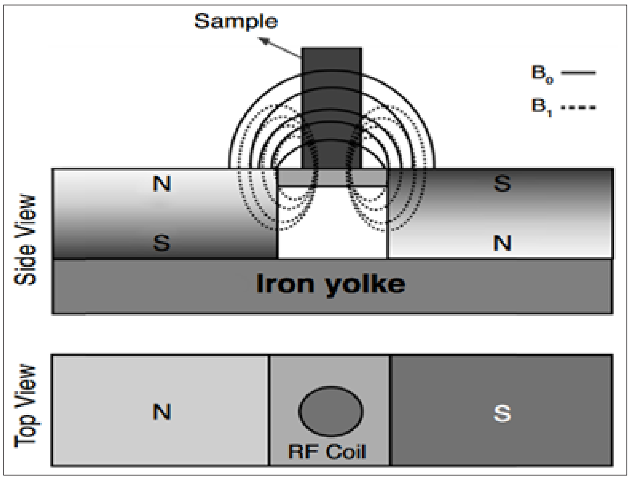

Figure 1: Schematic of MRI [7].

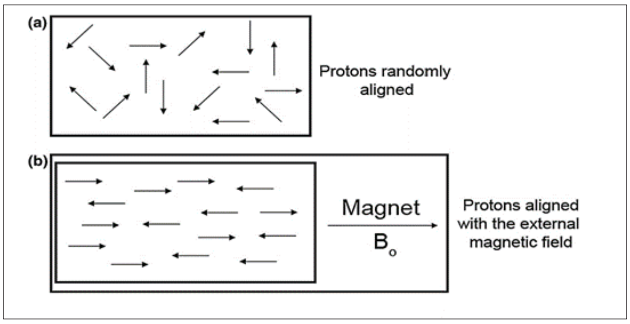

Figure 2: Schematic of proton direction with and without an external field [44].

Nuclei that exhibit nuclear magnetic resonance (NMR) include ^{1}H, ^{31}P, ^{15}N, and ^{23}Na. Magnetic resonance techniques are specifically designed to estimate the macroscopic magnetization of a material sample. In a magnetic resonance experiment, information is gathered by placing a sample within a homogenous external field denoted as B_0. The application of this field causes the nuclei exhibiting magnetic resonance to align and generate a small measurable magnetic moment. This induced magnetization is what makes MR techniques non-in-

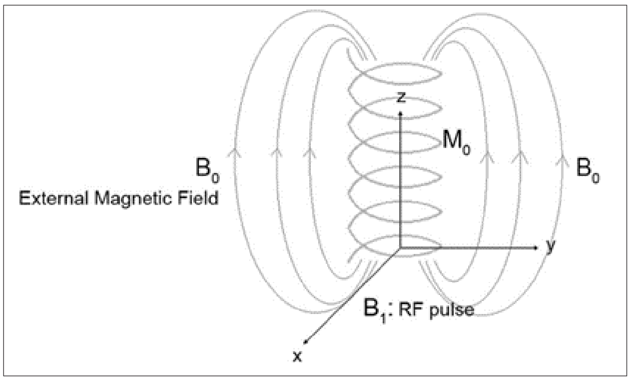

Figure 3: Schematic of magnetization occurred by placing a sample into an external field [44].

vasive. In many food research applications, a common spin-active nucleus resonates under specific conditions in the presence of a magnetic field. When an oscillating magnetic field at the correct frequency is applied, the nucleus resonates (precesses) about its equilibrium position. The frequency of the oscillating magnetic field required for resonance is known as the Larmor frequency ω0, defined by the Larmor equation (Equation 1):

$$\omega_0 = \gamma B_0 \qquad 1$$

In which ω0 represents the radio frequency (RF) in MHz, B_0 denotes the magnetic field strength in Tesla, and γ is the gyromagnetic ratio, a constant specific to each nucleus.

A secondary magnetic field (B_1) is applied as an RF pulse, causing the nuclei to transition into a non-equilibrium state. After this pulse, the excited nuclear spins release energy and return to the equilibrium state by precessing back to their original orientation at the Larmor frequency [20, 34, 45, 46].

The relaxation of magnetization towards the equilibrium state can be characterized by two relaxation time constants. Spin-lattice relaxation (T_1) entails the transfer of energy, often enthalpic, between the excited nuclear spins and their surrounding lattice. Spin-spin relaxation (T_2) involves the exchange of energy among similar nuclei and can be conceptualized as an entropic process [44, 47, 48]. Both time constants are essential in MRI experiments (Figure 4). Differences in relaxation times result in contrast in the NMR image and variations in both proton signal intensity and frequency within the localized spectrum [34].

Applications of MRI in the Evaluation of Internal Quality Factors in Food and Agricultural Products

MRI has proven to be a powerful method for evaluating internal quality aspects of food products (Figure 5). The assessment of agricultural and food product quality has been extensively studied using MRI [4, 15, 49-51].

Process control

Foods are dispersed multiphase systems (Suspensions, foams, emulsions, and porous solids) [52]. NMR has been widely advocated as a sensor for process control, owing to its exceptional specificity and capability to quantitatively assess internal properties. In the context of food systems, especially fresh fruits and vegetables, consumer purchase decisions are often influenced by external appearance. Nonetheless, internal quality holds utmost significance for consumption and production objectives [53].

NMR parameters are sensitive to plant issue's structure and compositions and different issues causes image changes in MRI. By MRI, it is not possible to obtain subcellular information, but does provide apparent relaxation parameters. Many times, in different fruit and vegetables textures, there are small spaces filled with gas, water or their combinations. Gas and water have different magnetic characteristics and combination of these features, causes irreversible signal loss during echo time [15].

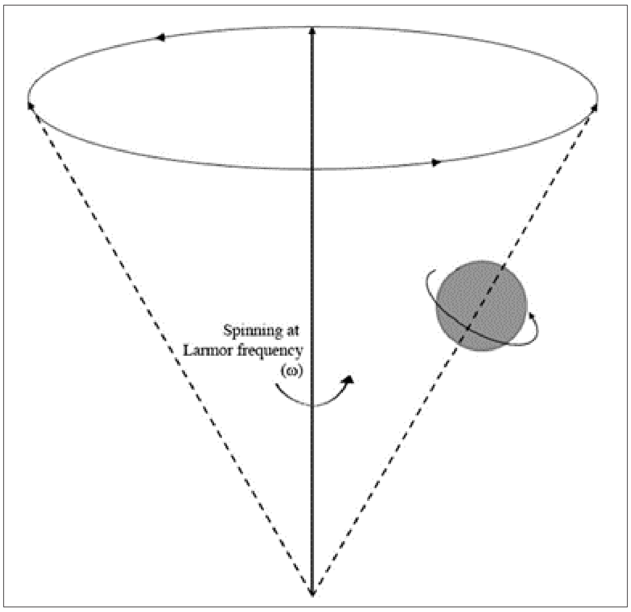

Figure 4: Schematic depicting the processional motion of protons [44].

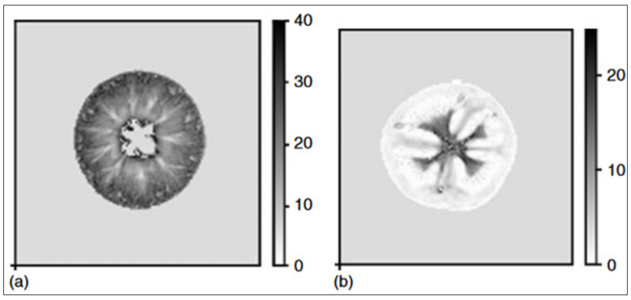

Figure 5: Porosity detection in apple interior texture **(a)** and a tomato **(b)** using MRI [15].

The dried fruit processor needs information on soluble solids content to predict the quality of the final product. In addition to the concentration of constituents in fruits or vegetables, various internal defects present challenges for detection using optical sensors. MRI is notably effective in identifying internal defects such as hollow heart in potatoes, brown center and bruises in apples, and freeze damage in oranges [53, 54]. Several research studies have focused on process control in fruits and vegetables, including issues like water core disease in apples [55], the mealiness in apple and peach [56, 57], core breakdown in pear [58, 59], dehydration of radishes, kiwi fruit, and strawberry [59-63].

Drying

Monitoring drying process with MRI has been done on various whole fresh agricultural products. However, due to their heightened morphological complexity, there have been no efforts to model the outcomes using diffusion equations. Significant research has been dedicated to optimizing drying parameters for beans. Key objectives for process enhancement include enhancing water intake rates and water-holding capacity, while minimizing starch matting and bean splitting [53, 64, 65].

Damage to beans, such as cracked seed coats, can lead to various issues including reduced yield, oxidation of lipids, canned products starching, and increased thermal requirements for canning. The processing quality of dried beans is typically evaluated through water content measurement [66, 67].

Rehydration

Many dried foods need to be rehydrated by consumers before consumption, underscoring the need to guarantee satisfactory quality in the rehydrated product. Rehydrated food quality depends on the freezing method, because it has considerable effect on ice crystal size, freezing rate, and porous structure. A thorough MRI investigation into the rehydration of spaghetti has been documented. In the case of spaghetti, factors like pastiness and unity after rehydration serve as main factor of quality, and rehydration should not be overly slow [68].

The spaghetti wheat used and the temperature during extrusion process are two main important factors. The extrusion process can involve durum wheat with hard texture and high gluten content, soft wheats, or these two mixtures, each choice affects significantly on the kinetics of rehydration. In raw materials choosing step, MRI can be useful for both optimizing the raw materials selection by providing detailed insights into the moisture profiles, considering the final spaghetti quality during rehydration and cooking time [68, 69, 70].

Freezing and freeze-thawing

Crystallization process consists of two steps: nucleation and the growth of the crystals. The nucleation stage has two sub-divisions: primary nucleation and secondary nucleation (when new crystals are formed in the presence of formerly created crystals) [31].

Freezing, whether through crystallization or amorphous crystals development, reduces mobility of molecules, thereby increasing relaxation rates and decreased the MR signal, with limited resolution [31]. There are some limitations in using MRI to evaluate freeze products. The contrast between fat and muscles is not considerable immediately after animal slaughter but increases during ripening because of drying muscles during time [15]. Besides, the environmental temperature can affect the final result of MRI. Fat usually starts crystallization under 4 °C and causes some errors in signals during echo time [15].

In the food samples always, there are movements of the freezing interface, including chicken, beef, meat, potatoes, peas, and corn [71]. Normally, food freezes in a vast range of temperatures, while each temperature below zero characterized by a specific ratio of liquid water to ice and may cause some damage to the animal or plat texture [72]. This phenomenon occurs because the biopolymers' surface changes the dynamic and structural state of adjacent molecules of water matrix, preventing them from forming a regular ice lattice. As a result, a portion of solution with water is still liquid even at temperatures lower than -150 °C [31]. Due to varying biopolymer and solute compositions, different subcellular organelles within cellular fruit and vegetable tissues display unique freezing behaviors. For instance, starch granules and cell walls and starch granules in potatoes retain liquid water even at -25 °C. This inherent intricacy makes it challenging to predict the quantity of liquid water and ice present at temperatures below freezing, leading to uncertainty about the latent released during the freezing process [73, 74]. Different texture damages after freezing process, is not uniform and is completely depends on the method, temperature, and time of freezing. The issue damage causes less restriction of the water molecules that could be monitored by longer T2 relaxation and can be identified [31, 73, 75, 76]. By the way, the accurate segmentation of tissue into damaged and non-damaged regions by MRI comes with a challenge [73].

MRI plays a crucial role in elucidating the complicated freezing phenomenon by imaging the real-time of ice and liquid water spatial distribution. Ice has an extremely limited transverse relaxation time, it does not contribute significantly to the MRI signal, thereby allowing only the unfrozen water to affect image intensity. In the realm of food freezing, MRI data provides insights into the local ratio of liquid-to-solid water phases [77]. Accurate enthalpy data derived from MRI can only be reliably obtained when the system is in equilibrium. In situations where the system is in a metastable state, such as being subcooled, the enthalpy estimated from MR data may be inaccurate. Different experiments have shown that temperature changes greater than 3 °C can lead to errors in the final results. Preparing samples with a size of 2.5 mm could solve this problem [78]. Non-invasive and continuous monitoring of the freezing process using MRI has already been investigated across a variety of food types, including orange juice, beef, carrots, chicken, corn, dough, berries, potatoes, fish, and baked products [75, 79, 80].

Food rheology

MRI offers unique advantages in flow studies of suspensions that are concentrated or colloidal and other cloudy liquids where optical methods like laser doppler anemometry or visual inspection of moving particles is impossible. Integrating flow imaging sequences with pulse sequences to NMR parameters like relaxation time, diffusion coefficients, or chemical shifts offers the theorical possibility to simultaneously map velocity alongside other parameters such as concentration, temperature, or reaction rate [7, 81].

The flow feature is one of the most important characteristics in granules or fluid food products. Usually, it has non-Newtonian nature and is important for designing and optimizing the quality and sensory properties of foods, besides their efficient processability [82].

Several MRI flow techniques enable non-invasive observation of velocity profiles and residence times during completely protected processes, for instance, aseptic, and extrusion. MRI techniques useful for determining velocities and residence times generally fall into two categories: time-of-flight (ToF) and velocity-encoded techniques. Presently, ToF techniques have received more attention in food science journals and are more accessible for non-physicists to understand [34, 83, 84]

Evaluation quality and quantity of some plant products like fruits, seeds, cereals, tubers, and vegetables is very difficult and for transformation in food processing and shelf-life studies, MRI is a suitable technique because of its possibility in quantitative assessment of water and oil migration [82].

Crystallization and melting phenomena

MRI has facilitated direct monitoring of the crystallization kinetics of fats in bulk or in fat/water emulsions containing various triglyceride species [53, 54]. Integrating MRI data with calorimetric studies can effectively test the assumption of local equilibria in calculations of freezing rates and help estimate potential errors under different freezing conditions [85-87]. MRI has been utilized to study the liquefy and oiling-off processes in cheddar cheeses, encompassing both classic and low-fat varieties. Usually, fat and water crystals in under-tempered products could not form uniform as well-tempered ones. In some foods that mostly contain low saturated triacylglycerols, crystals form a crystalline microstructure between the center and outer part of product. During storage, because of migration of low saturated triacylglycerol, the concentration changes. In this period, crystals tend to form in the outer layer of food. By the way, MRI monitoring is a helpful technique in quality evaluation [88-91].

Conclusions

MRI is an expanding field with significant potential to address questions and enhance understanding in food science and processing beyond what traditional techniques can achieve. MRI provides a versatile, noninvasive, nondestructive, and green method of experimental approach for studying various aspects of food processing. This discussion has covered MRI applications in food science including freezing and crystallization, diffusion, emulsions, drying, syneresis, and flow.

One limitation of using MRI is its inability to resolve subcellular information. In complex natural foods, various parts within intercellular spaces and plant textures induce irreversible signal loss during echo time, leading to testing errors.

In animal textures, this technique faces different challenges, particularly related to the test environment temperature. Images can be inaccurate at temperatures below 4 °C because the fat in carcasses partially crystallizes, resulting in low signals. MRI monitoring during the freezing process has shown varying results, as the images differed with temperature changes exceeding 3 °C. Recently, researchers have reported that reducing the sample size could solve this problem.

During the freezing process, many parts of plant or animal textures can be damaged, and distinguishing between damaged and undamaged parts is impossible with MRI monitoring. This technique has limited resolution and sensitivity but is very fast and needs very little sample preparation.

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None.

Conflict of Interest

None.

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