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An investigation of the structural aspects of the tomato fruit by means of quantitative nuclear magnetic resonance imaging

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Abstract

In this study, magnetic resonance imaging (MRI) was applied to study the structural aspects of the tomato fruit. The main study was performed on tomatoes (cv. Tradiro) using a 0.2-T electromagnet scanner. Spin-echo images were acquired to visualize the tomato macrostructure. The air bubble content in tissues was evaluated by exploiting susceptibility effects using multiple gradient echo images. The microstructure was further studied by measuring spin–spin (T_2) and spin–lattice (T_1) relaxation time distributions. Nuclear magnetic resonance relaxometry, macro vision imaging and chemical analysis were used as complementary and independent experimental methods in order to emphasize the MRI results. MRI images showed that the air bubble content varied between tissues. The presence of gas was attested by macro vision images. Quantitative imaging showed that T_2 and T_1 maps obtained by MRI reflected the structural differences between tomato tissues and made it possible to distinguish between them. The results indicated that cell size and chemical composition contribute to the relaxation mechanism.

Keywords: MRI; NMR; Plant; Tomato; Spin–lattice relaxation; Spin–spin relaxation; Air bubble

1. Introduction

Much research has been carried out in the tomato fruit to determine the factors involved in end-use quality such as sensory texture properties. The texture of a fleshy fruit is affected by both the cellular structure and the biochemical composition of the tissue. Tissue organization, depending on cell morphology, cell arrangement and cell and tissue properties, is also thought to influence the mechanical properties of plants. In this context, magnetic resonance imaging (MRI) can provide indirect or direct information both at the cell and macroscopic levels with the advantage of nondestructive analysis. This is particularly interesting for investigating aspects such as fruit ripening or disorder development.

MRI has been used for nondestructive studying of the internal structures and micro dynamics of water in various fruit and vegetable tissues [1]. Quantitative MRI is particularly suitable for plant investigations as the relaxation times and proton density are known to be strongly related to the microstructure of plant tissues. However, only a few MRI studies of tomato fruit have been reported until now. Saltveit [2] used qualitative MRI to investigate tomato ripening and showed that differences in maturity can be seen in the images. Ishida et al. [3] measured spin–lattice relaxation time (T_1) in a single green and in a single mature tomato fruit and indicated that T_1 of tissues changes between the two ripening stages. Iwahashi et al. [4] investigated the heat stress in tomato fruits by qualitative MRI and measured spin–spin relaxation time (T_2) in the pericarp and locular tissues before and after thermal process. Finally, Gonzalez et al. [5] used MRI anatomical images to evaluate internal structural changes of tomato during compression. Otherwise, nuclear magnetic

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resonance (NMR) was used to measure T_2 and water diffusion coefficient in the outer pericarp [6]. Despite results of these investigations, any quantitative MRI or NMR study of both T_2 and T_1 relaxation parameters and proton density of all the tomato fruit tissues has been reported up to now, which prevents a reliable image interpretation. Moreover, to our knowledge, tissue characteristics such as gas bubble content have not been investigated until now.

The first aim of the present study was to perform a detailed investigation of the tomato fruit structure by means of spatially resolved quantitative measurements of T_2 and T_1 relaxation times and to evaluate the air bubble content by exploiting susceptibility effects in the multiple gradient echo (GE) sequences. Our intention was to provide a reference for further investigations of aspects such as tomato ripening or disorder development. The second aim was to investigate physical parameters that influence relaxation processes. NMR relaxometry was used to measure relaxation times without the corrupting effects of imaging gradients, contributing therefore to understanding their influence on MRI T_1 and T_2 mapping. Macro vision technique, chosen over conventional microscopy because of large dimensions of tomato cells, made it possible to correlate the results of the MRI study with cell size and organization and to visualize air bubbles in tissues. Water and sugar contents were measured in the tomato fruit tissues in order to explain the differences in T_2 and T_1 between tissues. The complexity of the interpretation of the MRI image contrast was finally demonstrated on a spin-echo (SE) image by taking into account the relaxation times, proton density and air bubble distributions.

2. Materials and methods

2.1. Tomatoes

Nineteen Tradiro tomatoes provided by the Centre Technique Interprofessionel des Fruits et Légumes (CTIFL, France) were used in this study. The fruits were picked at their late green stage (tomato color code 3–4, CTIFL, France) and stored in a constantly aerated ripening chamber under controlled conditions (18°C and 55% RH) for 9 days. All MRI and NMR macro vision experiments and water content measurements were performed on the same day at the end of this period. The tomatoes were then red, firm and without any external defects.

2.2. Magnetic resonance imaging

2.2.1. Image acquisition

Measurements were performed on a 0.2-T MRI scanner (Magnetom Open, Siemens, Erlangen, Germany) equipped with a multipurpose flexible receiver coil (MP_S). The maximum imaging gradients were 15 mT/m along all axes. The fruits were positioned in the ripening chamber in a specifically designed experimental thermoinsulated support in order to guarantee a constant temperature (18°C) for the tomatoes during measurements. The support was closed with a cap for at least half an hour before placing it in the magnet. The temperature of the thermally insulated Faraday cage was also set at 18°C.

The MRI experiments were performed on nine tomatoes. For each tomato, an SE "morphological" image of the median equatorial plane was acquired with the following parameters: echo time (TE)=15 ms, recycle time (TR)=200 ms, matrix size=128^2 pixels, field of view (FOV)=90^2 mm^2, slice thickness=3 mm, 15 averages resulting in a total acquisition time of 6 min 40 s.

For the other images, the same plane was studied with the following geometrical parameters: matrix size=128^2 pixels, FOV=128^2 mm^2 and slice thickness=5 mm.

Air distribution in the tomatoes was studied from two spoiled GE images acquired with the following parameters: flip angle=40°, TR=1 s, 2 averages and TE_1=9 ms and TE_2=40 ms, for the first and second images, respectively, resulting in a total acquisition time of 4 min 18 s.

T_1 relaxation and corresponding signal intensity at equilibrium $M_0(T_1)$ maps were measured using the TOMROP (T One by Multiple Read-Out Pulses) sequence [7] on only three of the nine tomatoes studied (because of the long acquisition time). The parameters of the sequence were as follows: TI=210 ms, N_{TI}=32, angle=10°, TR=10 s, 3 averages and acquisition time=1 h 4 min.

T_2 relaxation and corresponding signal intensity at equilibrium $M_0(T_2)$ maps were obtained from multispin-echo (MSE) sequence with the following parameters: first echo equal to interecho spacing TE=30 ms, number of consecutive echoes N=32, TR=10 s, 2 averages and acquisition time=43 min.

Finally, one extra tomato fruit was used to acquire T_2 maps with the same parameters as described below, except for TE, which was successively set at 30, 50 and 90 ms. The aim of the latter experiment was to study the effects of TE spacing on T_2 measurements.

The correction for the nonuniformities of the MRI scanner was performed by division of pixels of MR tomato images by the corresponding pixels of the water phantom images. Phantom images were acquired at the same settings as the corresponding tomato images, except for the increased number of averages and TR.

The magnitude of the MSE and TOMROP image series was fitted on a pixel-by-pixel basis using corresponding monoexponential functions, via the Levenberg–Marquardt criterion for chi-square minimization implemented on Scilab software. MSE and TOMROP data were fitted with a two-parameter [8] and a three-parameter [7] function, respectively. The standard error maps of each fitted parameter were computed for each T_2 and T_1 map.

Regions of interest were drawn manually from the T_2 maps that corresponded to a homogeneous region in each tissue and applied to T_2, $M_0(T_2)$, T_1, $M_0(T_1)$ and GE images. The average intensities and corresponding standard deviations were measured within these regions. The standard