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Magnetic resonance imaging of objects with dipolar-broadened spectra using soft excitation pulses

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Abstract

Feasibility of acquiring high-resolution 3D NMR images of objects with dipolar-broadened spectra by using soft excitation pulses is experimentally demonstrated. The models are liquid-crystalline phantoms and a pencil eraser. The pulse sequence is a standard 3D gradient-echo sequence.

Keywords: MRI; Soft excitation; Liquid crystal; Polymer

1. Introduction

Recently, we have demonstrated that long-lived coherent response signals produced by long and weak excitation pulses can be used in NMR imaging, and presented 1D profiles of model samples as a "proof of principle" [1]. The goal of this work is to show that intensity of the coherent response signals is, in some cases, sufficient to produce high-resolution 3D images of objects with dipolar-broadened conventional NMR spectra.

In NMR imaging, the achievable spatial resolution Δx in x-direction can be estimated as [2]

$$\Delta x = 2\pi\Delta f/(\gamma G_x), \quad (1)$$

where Δf is the NMR linewidth, G_x is the magnetic field gradient applied in the x-direction and γ is the nucleus gyromagnetic ratio. Therefore, high spatial resolution requires either narrow NMR signals or strong magnetic field gradients. NMR lines are very narrow in liquids (Δf~0.1–10 Hz), where anisotropic dipolar couplings are averaged out by fast molecular motions. Today, most of MRI applications utilize narrow NMR signals of liquids. The spatial resolution can reach 1 μm for small objects (NMR microscopy [3]). With the existing NMR imaging techniques, spatial resolution is considerably less for solids or "soft solids" where, in contrast to liquids, the dipole–dipole interactions between nuclear spins are not averaged completely by molecular motions.

In solids, NMR lines are 3–5 orders of magnitude broader than in liquids, and one would expect proportionally degraded spatial resolution. However, there have been significant efforts to create efficient NMR imaging techniques for objects with dipolar-broadened spectra. Improved resolution can be achieved with line narrowing using multipulse sequences [4–6], or with very strong gradients of stray field of a magnet [7,8]. The line-narrowing multipulse sequences based on magic echo [9] are especially convenient for imaging application [10]. Among systems with broad spectra, studied with MRI, are polymers [11–17], porous materials [18,19], other hetero-phase systems [20], biomedical polymers [21–25] and semisolid materials [26]. A review of imaging techniques for solid materials can be found in Ref. [27]. Despite a considerable progress, spatial resolution in solid samples remains much less than in liquids. In addition, a necessity of using strong RF and/or gradient pulses creates serious technical challenges for imaging large objects.

We have found that long and weak excitation pulses can produce long-lived collective coherent response signals in systems with dipolar-broadened NMR spectra [28,29]. Larger intensities of the signals are found in cases when the dipole–dipole couplings are partially averaged by molecular motions [30]. Such collective response signals

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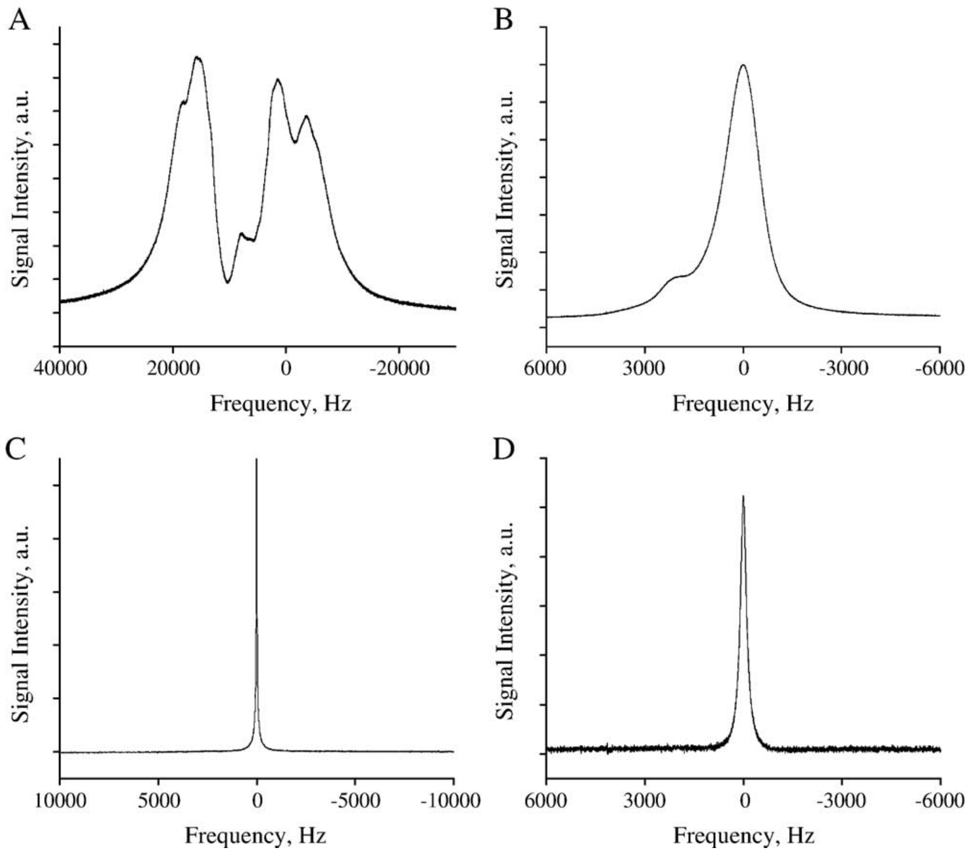

Fig. 1. Conventional ^{1}H NMR spectra of 5CB (A) and pencil eraser (RoseArt X500) (B) with 5.5-μs 90° pulse; (C) ^{1}H NMR spectrum of 5CB excited with 100-ms pulse of RF amplitude $\gamma B_1/2\pi=55$ Hz, acquisition delay is 200 μs, the linewidth is 37 Hz; (D) ^{1}H NMR spectrum of the eraser excited with 14-ms pulse, $\gamma B_1/2\pi=25$ Hz, acquisition delay is 200 μs, the linewidth is 220 Hz.

are excited at the generator rather then the Larmor frequency and, therefore, carry no spectroscopic information. But they are suitable for encoding spatial position in the presence of gradients and can be used in diffusion measurements [31] or imaging [1]. In fact, excitation at the generator frequency has an extra advantage of being insensitive to a static field inhomogeneity caused by nonperfect shims or magnetic susceptibility variations.

The long-lived response signals are destroyed by hard RF pulses, and, therefore, no refocusing 180° pulses can be used in the imaging pulse sequence. At the same time, a standard gradient-echo pulse sequence can be used without any modification except that the only hard 90° pulse is replaced by a soft excitation pulse.

2. Materials and methods

All experiments were carried out with a Varian Univty/Inova 500 MHz NMR spectrometer equipped with a 5-mm Varian probe with three orthogonal gradients of maximum strength 60 G/cm in z-direction and 28 G/cm in x- and y-directions. We have chosen three models for the present demonstration. Two of them are liquid-crystalline phantoms and the third one is a pencil eraser of RoseArt X500 mechanical pencil. Liquid crystal 5CB was purchased from Aldrich and used without further purification.

The phantom in Fig. 2 is a 5-mm flat-bottom NMR tube filled with 5CB, and there is an axially symmetric Teflon insert inside of the tube. The phantom in Fig. 3 is a round-bottom 5-mm NMR tube and coaxial inner tube with OD 3.3 mm/ID 2.3 mm. Both tubes are filled with 5CB. For the image in Fig. 4, a commercially available pencil eraser, product of RoserArt Industries, a cylinder of 5-mm height and 4-mm diameter, was placed in a standard 5-mm NMR tube.

The gradient-echo 3D multislice acquisition protocol of Varian's VNMRJ software was used for all phantoms in this work. For 3D image of 5CB in Fig. 2, the repetition time T_R is 2.1 s. The data matrix 128×64×64 covers FOV of 16×10×10 mm^3. Total acquisition time was 66 h and 54 min with 28 averages. The thickness of slices presented in Fig. 2 is 156 μm. The maximum strength of applied gradients is 7.1 G/cm for read-out gradient and 17.0 G/cm for phase-encoding gradients.

The image in Fig. 3 was obtained with T_R=2.7 s. The data matrix is 128×64×32 with FOV of 8×8×10 mm^3. The applied gradients are 13.0 G/cm for the read-out gradient and maximum of 11.9 and 4.8 G/cm for phase-encoding