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Spectroscopic imaging from spatially-encoded single-scan multidimensional MRI data

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Abstract

We have recently proposed a protocol for retrieving multidimensional magnetic resonance images within a single scan, based on a spatial encoding of the spin interactions. This methodology relies on progressively dephasing spin coherences throughout a sample; for instance, by sweeping a radiofrequency pulse in the presence of a magnetic field gradient. When spins are suitably refocused by a second (acquisition) field gradient, this yields a time-domain signal reflecting in its magnitude the spatial distribution of spins throughout the sample. It is hereby shown that whereas the absolute value of the resulting signals conveys such imaging information, the hitherto unutilized phase modulation of the signal encodes the chemical shift offsets of the present speciae. Spectroscopically-resolved multidimensional images can thereby be retrieved in this fashion at no additional expense in either experimental complexity, sensitivity or acquisition time—simply by performing an additional analysis of the collected data. The resulting approach to single-scan spectroscopic imaging can also incorporate "RF shimming" compensating abilities, capable of providing high-resolution spectral and high-definition imaging data even under the presence of substantial magnetic field inhomogeneities. The principles of these methodologies as applied to spectroscopic imaging are briefly reviewed and compared against the background of traditional Fourier-based single-scan spectroscopic imaging protocols. Demonstrations of these new multidimensional spectroscopic MRI experiments on simple phantoms are also given.

Keywords: Spectroscopic imaging; Ultrafast MRI; Spatial encoding; Inhomogeneity compensation; EPSI

1. Introduction

Nuclear magnetic resonance (NMR) finds its two main areas of application in the fields of chemical analysis, and in the non-invasive spatial visualization of spin densities [1–3]. When operating in an analytical mode NMR affords information about the nature and the quantity of the analytes being scrutinized, according to the peak positions and the intensities appearing in its spectrum [2]. Monitoring these peaks benefits from the highest possible magnetic field homogeneity, which in turn leads to the sharpest line shapes and to an optimal site resolution. By contrast, when operating in a spatial visualization (MRI) mode, it is the spins' positions that are being sought [3]. These are usually mapped into frequencies with the aid of auxiliary field gradients translating the spins' coordinates into offsets in a one-to-one fashion [4,5]; positions are thereby imprinted in the NMR line shapes at the expense of a significant broadening of the resonances. The needs placed by the spectroscopic and imaging modalities imply that extracting both the chemical nature of a spin as well as its position within the sample, is associated with conflicting demands that do not suit a one-dimensional NMR acquisition. On the other hand spectroscopic imaging measurements can be achieved without complications by relying on multidimensional experiments [1–3,6], which separate and correlate what may otherwise be conflicting modes of observation. The resulting experiments are usually characterized by at least one spectral and up to three spatial dimensions [7–10], and their usefulness in *in vivo* investigations has been demonstrated in a number of contexts [11–14].

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Due to its inherent multidimensional nature, spectroscopic imaging will usually demand relatively longer acquisition time than its one-dimensional NMR counterparts. A variety of ways have consequently been discussed for accelerating this kind of experiments [15,16]. Many of these variants rely on methods stemming from Mansfield's echo-planar imaging (EPI) and echo-planar spectroscopic imaging (EPSI) propositions [17,18]. These are "ultrafast" approaches relying on oscillating the imaging gradients so as to monitor sizable volumes of the hybrid k/t-space within a single scan; applying a Fourier transform (FT) on the resulting signals yields then the desired correlations between the position-derived and the chemical-shift-derived spin precession frequencies. In addition to such strategies derived from "walks" in the k or k/t-spaces [19,20], we have recently discussed alternative approaches to the acquisition of multidimensional NMR data within a single scan that rely on encoding the spins' evolution along an ancillary, spatially-encoded domain [21,22]. The resulting "ultrafast" nD NMR protocol is applicable within a purely spectroscopic and/or an imaging scenario, and it is the latter that constitutes the starting point of the present work. As explained elsewhere in further detail [23] spatially-encoded MRI retrieves a multidimensional image within a single scan, by applying an external magnetic field gradient that spreads out the resonance frequencies, in conjunction with a frequency-incremented excitation or inversion of the spins. This imposes a quadratic phase encoding $\phi_e(r) \approx Cr^2$ on the spins which, when subsequently read out under the presence of an acquisition gradient G_a, results in a signal whose modulus is directly proportional to the spin density $\rho(r)$ of the object in question. Such imaging principle operates without subjecting its data to a FT, and it can be exploited in a number of ways to obtain 2D NMR images within a single scan [24]. When comparing the method's performance against EPI-based schemes, however, the results offer a mixed outcome. On one hand it is clear that EPI schemes make a more efficient use of the available gradient action k, towards the reading out of the images. On the other hand it was shown that the built-in selectivity underlying spatially-encoding provides a route to reduce field inhomogeneity distortions, which may otherwise affect EPI's low-bandwidth dimension.

The present work explores a different aspect related to the application of spatial encoding principles within an imaging scenario, stemming this time from the method's ability to differentiate between various chemical shifts contributing to the image—at no additional expense in the experiment's complexity. It is here demonstrated that in spatially-encoded MRI, the presence of multiple chemical sites will create a modulation of the phases characterizing the read-out signals. Such phase effects were heretofore disregarded, as the image-reconstruction procedure solely involved a magnitude data calculation. Yet it is shown that by applying a simple FT-based processing on the spatially-encoded data, this phase information can be exploited for the sake of retrieving an NMR spectrum as well as its associated spatial distribution, yielding in effect a new approach to single-scan spectroscopic imaging. Performancewise the resulting approach compares favorably with EPSI-type single-scan experiments, even if its scope of applications may be more limited. It is also shown that in this kind of spectroscopic imaging, high-resolution spectroscopic and high-definition MRI acquisitions are still feasible even if spins are subject to sizable distortions of the ideal B_o static magnetic field.

The operation of spatially-encoded ultrafast spectroscopic imaging experiments are illustrated in this work for a number of simplified scenarios. The methodology's principles are first reviewed for unidimensional objects; examples of the method's operation are given, and its relative merits and potential artifacts are briefly assessed. We then describe the method's extension to higher spatial dimensions, with experimental demonstrations and comparisons against EPI results on a simple phantom. Finally, we discuss and demonstrate the method's ability to afford its spectroscopic imaging information even in the presence of field inhomogeneities, both using basic approaches as well as with a new sequence designed to better handle the presence of multiple chemical sites.

2. Single-scan spatially-encoded spectroscopic imaging on one-dimensional objects

2.1. Basic treatment

We address first the simplest application of spatial encoding to spectroscopic imaging, dealing with a sample characterized by a discrete spectral distribution of chemical shifts $I(\Omega)$, each of which possesses a one-dimensional spin-density profile $\rho_\Omega(z)$. Traditional imaging retrieves the spins' spatial distribution by working on-resonance and monitoring the effects of a constant gradient on the signal following a broad-band excitation pulse (Fig. 1a), whereas ultrafast 2D EPSI seeks to correlate the z and Ω distributions by homogeneously exciting the spins, and then monitoring their signals while under the effect of an oscillating

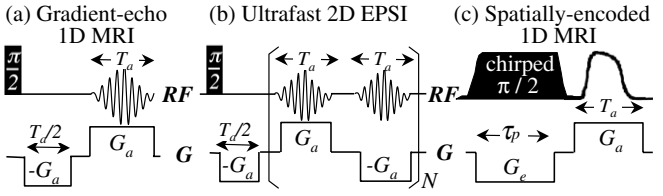

Fig. 1. Imaging and spectroscopic imaging single-scan schemes considered in this study. (a) Conventional gradient-echo k-domain scheme leading to a $\rho(z)$ image after FT. (b) Echo-planar spectroscopic imaging (EPSI) approach leading to shift-resolved $\rho_\Omega(z)$ spatial distributions via the acquisition of multiple (N) gradient-echo signals. (c) Non-FT scheme introduced in Ref. [23] whereby positions initially encoded via a chirped $\pi/2$ pulse acting in the presence of a gradient, are subsequently read out in the time domain by an acquisition gradient. This work demonstrates how 2D $\rho_\Omega(z)$ spectroscopic imaging distributions can also be retrieved from the resulting $S(t)$ signals.