Journal of Magnetic Resonance 231 (2013) 126–132

Contents lists available at SciVerse ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

Restricted k-space sampling in pure phase encode MRI of rock core plugs

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ARTICLE INFO

Article history:
Received 25 January 2013
Revised 30 March 2013
Available online 12 April 2013

Keywords:
Optimal sampling
k-Space trajectory
Hybrid-SESPI
SPRITE
Core plugs

ABSTRACT

In the study of rock core plugs with multidimensional MRI, the samples are of a regular cylindrical shape that yields well defined intensity distributions in reciprocal space. The high intensity k-space points are concentrated in the central region and in specific peripheral regions. A large proportion of the k-space points have signal intensities that are below the noise level. These points can be zero-filled instead of being collected experimentally. k-space sampling patterns that collect regions of high intensity signal while neglecting low intensity regions can be naturally applied to a wide variety of pure phase encoding measurements, such as T_2 mapping SESPI, hybrid-SESPI and SPRITE, since all imaging dimensions can be under-sampled. With a shorter acquisition time, as fewer experimental data points are required, the RF and gradient duty cycles are reduced, while the image SNR is improved.

1. Introduction

MRI of fluids in porous media has historically been considered challenging due to the susceptibility variations and paramagnetic impurities within the samples. Pure phase encode techniques have proven to be robust in their ability to generate true fluid content images in porous media [1–4]. The acquisition time is however long with pure phase encoding as only one k-space point is typically acquired with each RF excitation.

Single Point Ramped Imaging with T_1 Enhancement (SPRITE) [1] has been employed to image short relaxation time systems for many years with great success. In SPRITE, the phase encoding gradients are ramped in discrete steps to reduce imaging times and minimize gradient vibration. Low flip angle RF pulses are employed to cover the sample bandwidth which arises from the high magnetic field gradients required for short encoding times. This yields a sub-optimal Signal-to-Noise ratio (SNR), especially at low static field.

1D Hybrid-SESPI [2] was proposed by Li et al. as a modification of the Spin Echo Single Point Imaging (SE SPI) method [5] to increase the measurement sensitivity, defined as SNR over the square root of time. Phase encoding and phase unwinding gradients were required to separately encode each echo in a multi-echo CPMG pulse train. However, 1D imaging will not reveal sample structure for heterogeneous samples that are not radially symmetric. Higher dimensionality MRI of rock core plugs is therefore highly desirable. A simple extension to 2D Hybrid-SESPI is challenging. The k-space points are sampled in clusters, each cluster is termed an interleaf, corresponding to each signal excitation in Hybrid-SESPI. The number of interleaves is limited by the acquisition time, as a relaxation delay of $5 \times T_1$ is required for density imaging, and the number of k-space points within each interleaf is restricted by the sample T_2 which may cause image blurring. k-space undersampling can be exploited to mitigate the problem.

Undersampling k-space has been a popular subject in the MRI literature for at least 20 years [6–8]. The commonly employed strategies in spin-warp imaging are based on undersampling k-space line by line. Since pure phase encode techniques sample k-space point by point, there are fewer restrictions, and each of the imaging dimensions can be under-sampled.

Geometric k-space sampling patterns are very natural and are routinely employed in centric scan SPRITE [9,10]. Sampling patterns which utilize radial, spiral, conical or sectoral trajectories omit the k-space points outside a circle or sphere of radius equal to half the matrix size in a Cartesian representation. In practice, some k-space points in proximity to the origin are also omitted. This approach generally works well for any sample shape, and in particular for spherical samples. Approximately 20% and 75% of the k-space data points are omitted in 2D and 3D centric scan SPRITE measurements, respectively.

Prior knowledge of the sample shape enables the design of more efficient sampling patterns. Parasoglou [11] determined the rank order of k-space point intensities by a sample binary image, and assumed the rank order remained the same during the dynamic moisture absorption process. Romanenko[12] obtained the k-space mask for high intensity points in a density imaging measurement and applied it in the readout of a magnetization preparation experiment. Both experiments were pure phase encoding measurements based on model k-space intensities on a point-to-point manner neglecting the subtle changes in the sample, such as proton density

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http://dx.doi.org/10.1016/j.jmr.2013.04.001

variations and real/imaginary phases of the image, which affect the distributions of high intensity k-space points. This idea was first employed in frequency encoding MRI measurements by Serša [13]. Frequency encoding is vulnerable to off-resonance effects with imaging artifacts related to the k-space trajectory. Frequency encoding is also more demanding on the performance of gradient hardware, since fast and accurate switching is required to traverse k-space in an arbitrary trajectory.

The samples in our study are cylindrical rock core plugs that yield well defined intensity distributions in k-space. The high intensity k-space points are concentrated along the major axes and in selected peripheral areas. Restricted k-space sampling patterns, based on high intensity regions, are applied for 2D Hybrid-SESPI, and 2D and 3D SPRITE measurements to reduce the acquisition time, reduce RF and gradient duty cycles and to increase the measurement sensitivity. The images from the restricted k-space sampling measurements reveal more clearly the intermediate scale sample structure that we seek. Our focus is not pixel scale resolution, which is largely affected by noise. Restricted k-space sampling provides more reliable images, in most cases, for rock core plugs than those from compressed sensing [14] which is not included in the discussion of this paper.

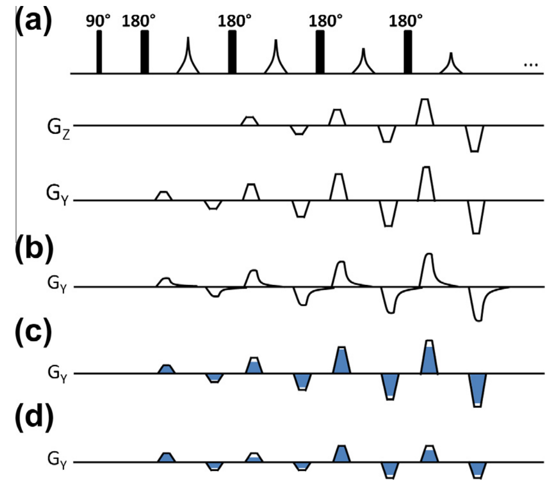

Fig. 2. The Hybrid-SESPI sequence. Each point of k-space is acquired by separately phase encoding individual echoes in a multi-echo acquisition. 64 gradient steps were employed for each dimension. (a) Pulse sequence with ideal gradient performance for 2D Hybrid-SESPI, (b) realistic gradient waveform in one dimension, (c) the net gradient experienced by the sample, and (d) the modified "repeated echo" scheme to mitigate the gradient leakage problem.

2. Theory

2.1. SPRITE

The SPRITE sequence, Fig. 1, is a pure phase encode measurement. The gradients are switched on and stabilized before applying the RF pulses. One single time domain point is collected following each RF excitation. k-space is sampled point by point, with all the imaging dimensions phase encoded. Centrically scanned sequences [9,10] are preferred when acquiring density-weighted images.

2.2. Hybrid-SESPI

The pure phase encode Hybrid-SESPI pulse sequence is illustrated in Fig. 2a. In 1D applications, each half of k-space is acquired by separately phase encoding individual echoes in a multi-echo acquisition. Bipolar phase encoding gradients are employed between refocusing 180° pulses to independently encode each echo. 90° excitation pulses are employed to maximize the signal intensity. The sensitivity is greatly improved compared to SPRITE [15]. This method is favorable for samples with long T_2 relaxation times, as the filtering caused by T_2 attenuation is moderate.

Multiple time domain points can be collected from each echo with a narrow filter width. The acquisition dwell time and number of time domain points are limited by the sample T_2. Since the magnetic field gradients have been switched off before the acquisition, the time domain points within each echo correspond to the same k-space point, so that they can be averaged to increase the SNR. These points should differ only by T_2^* attenuation, with negligible phase evolution. An image can be reconstructed from each set of time domain echo points.

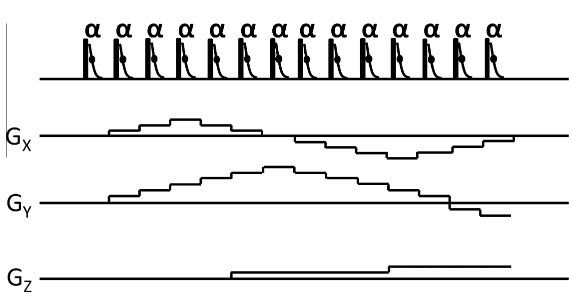

Fig. 1. The pure phase encode SPRITE sequence. The gradients are switched on and stabilized before applying the RF pulses. One single time domain point is collected following each RF excitation.

With ideal gradient performance the image series are expected to have the same FOV. However, due to long-lived eddy currents, there is residual phase evolution. This results in different FOV's among the image series, i.e. the images reconstructed from later echo points have smaller FOV's. The residual gradients also leak after the 180° pulse, applied 200 μs after the gradients being switched off, causing errors in phase accumulation. Fig. 2b illustrates a realistic gradient waveform in one dimension. The long-lived eddy current after the first gradient pulse causes phase evolution among the multiple time domain points in each echo. The residual long tail of the second gradient pulse, for phase rewinding, extends beyond the refocusing RF pulse, and results in phase error due to a portion of the gradient having switched polarity. The net gradient experienced by the sample is shown as the shaded areas in Fig. 2c. The error in the second echo arises from the partial phase cancellation and polarity switch in the gradient after the second 180° RF pulse.

Phase accumulation in the third echo is more accurate than for the second echo since the errors from the previous two pairs of bipolar gradients largely cancel. Similarly, phase encoding of all even echoes is corrupted while the odd echoes are relatively accurate. If the same amplitude gradients are applied twice for each k-space point to yield two sets of images, one from odd echoes and one from even echoes, the odd echo images are more reliable. The "repeated echo" scheme is shown in Fig. 2d. This strategy improves the image quality by ensuring the acquired points fall on the exact k-space grid, although it entails more T_2 related blurring as the effective echo time is doubled. It is suitable for long T_2 samples.

2.3. Sample geometry based restricted sampling

The idea of sample geometry based restricted sampling was outlined in our previous study [14]. It is based on the fact that the low frequency central portion of k-space, determining the overall image intensity and structure, has a higher amplitude than most of the high frequency periphery which contains information on the