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Achieving high spatial resolution and high SNR in low-field MRI of hyperpolarised gases with Slow Low Angle SHot

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ABSTRACT

MRI of hyperpolarised gases is usually performed with fast data acquisition to achieve high spatial resolutions despite rapid diffusion-induced signal attenuation. We describe a double-cross k-space sampling scheme suitable for Slow Low Angle SHot (SLASH) acquisition and yielding an increased SNR. It consists of a series of anisotropic partial acquisitions with a reduced resolution in the read direction, which alleviates signal attenuation and still provides a high isotropic resolution. The advantages of SLASH imaging over conventional FLASH imaging are evaluated analytically, using numerical lattice calculations, and experimentally in phantom cells filled with hyperpolarised ^{3}He–N_2 gas mixtures. Low-field MRI is performed (here 2.7 mT), a necessary condition to obtain long T_2^* values in lungs for slow acquisition. Two additional benefits of the SLASH scheme over FLASH imaging have been demonstrated: it is less sensitive to the artefacts due to concomitant gradients and it allows measuring apparent diffusion coefficients for an extended range of times.

1. Introduction

Two well-identified issues specific to MRI with hyperpolarised (HP) gases strongly affect sequence design and performance. Firstly, the initially available magnetisation is non-renewable and thus has to be used up efficiently. Small tip angle excitation, based on the FLASH (Fast Low Angle SHot) sequence [1] is most often used for radial or Cartesian k-space sampling, sometimes with a variable flip angle approach [2]. Secondly, high gas diffusivity leads to rapid signal loss and to image blurring, which sets joint constraints on the acquisition time and on the readout gradient. Increasing the spatial resolution of images implies acquiring more k-space data, using smaller tip angles and faster acquisition rates, at the expense of the signal-to-noise ratio (SNR). Alternative routes for HP gas lung MRI have been evaluated using single-shot sequences, such as EPI [3,4] or RARE [5–7], or using schemes similar to steady-state free precession imaging [8,9]. All these methods yield an increased SNR but are adversely affected by gas diffusion.

Here, we propose a dedicated k-space sampling scheme that can take better advantage of the available signal lifetimes T_2^* and is more immune to gas diffusion-induced attenuation since acquisition is performed with a moderate applied read gradient: Slow low-angle shot (SLASH) imaging is designed to combine high resolution and high SNR for HP gas MRI. Slow acquisition imaging of HP gases in lungs is expected to be most efficient at low or moderate applied fields (e.g., 1–100 mT), since high fields (e.g., 1.5 T and above) induce short values for T_2^* (of the order of 10 ms at 3 T) due to susceptibility-induced field gradients at alveolar scales [10–12].

The sensitivity of gas MRI to diffusion-induced attenuation indeed imposes limitations on acquisition parameters and sequence performance, but may also be exploited, in combination with imaging schemes, to probe geometrical restriction of gas diffusion by local sub-voxel structures. Measuring apparent diffusion coefficients (ADCs) is a standard characterisation method in various porous media and ADC of HP gas in lungs has been extensively studied in a wide range of situations. Short-range ADC, conveniently measured using short (a few ms) diffusion-sensitising bipolar gradient pulses, probe displacements of ^{3}He atoms on the order of the alveolar diameter. ADC maps associated with diffusion over large distances and long times, which provides more information on the connectivity of lung air spaces at the cm scale (that of the acinus), are usually obtained with less sensitive stimulated echoes [13] or spin tagging [6] methods. Short- and long-range ADC differ by as much as one order of magnitude; they appear to have different sensitivities and specificities to different lung characteristics and pathologies [13–16]. Using a double-echo imaging sequence can alternatively provide accurate ADC maps, in which the diffusion-sensitising gradient is the imaging read gradient. With SLASH imaging, the probed diffusion time in such double-echo schemes can potentially be varied over a broad range of values, especially

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