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Ultrashort echo time (UTE) imaging using gradient pre-equalization and compressed sensing

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ABSTRACT

Ultrashort echo time (UTE) imaging is a well-known technique used in medical MRI, however, the implementation of the sequence remains non-trivial. This paper introduces UTE for non-medical applications and outlines a method for the implementation of UTE to enable accurate slice selection and short acquisition times. Slice selection in UTE requires fast, accurate switching of the gradient and r.f. pulses. Here a gradient "pre-equalization" technique is used to optimize the gradient switching and achieve an effective echo time of 10 μs. In order to minimize the echo time, k-space is sampled radially. A compressed sensing approach is used to minimize the total acquisition time. Using the corrections for slice selection and acquisition along with novel image reconstruction techniques, UTE is shown to be a viable method to study samples of cork and rubber with a shorter signal lifetime than can typically be measured. Further, the compressed sensing image reconstruction algorithm is shown to provide accurate images of the samples with as little as 12.5% of the full k-space data set, potentially permitting real time imaging of short T_2^* materials.

1. Introduction

Ultrashort echo time (UTE) [1] imaging is a valuable technique for imaging short T_2 and T_2^* samples, however, its implementation is challenging and acquisition times can be long. Although the UTE pulse sequence is simple in theory, successful implementation requires accurate timing and a detailed understanding of the hardware performance [2]. This paper outlines a method to implement and optimize UTE to achieve accurate slice selection. The pulse sequence is also combined with compressed sensing (CS) [3] to reduce the acquisition time and potentially enable the study of dynamic systems.

UTE imaging was introduced to enable imaging of tissues in the body with short T_2 materials [1]. UTE has been used to study cartilage, cortical bone, tendons, knee meniscus and other rigid materials that would produce little or no signal from conventional imaging techniques [4–8]. However, few studies have been shown outside of medical imaging, despite widespread interest in short T_2 and T_2^* materials.

Many materials of interest in science or engineering applications will present short T_2 and T_2^* relaxation times due to heterogeneity. These systems could include chemical reactors, plants in soil, shale rock, or polymeric materials. In a polymer network the T_2^* can range from the order of 10 μs to 1 ms depending on the rigidity of the network [9]. The other systems present similarly short relaxation times. Thus, UTE will open new possibilities for studying a range of materials outside of the medical field.

Chemical reactors, such as fluidized beds [10,11], are particularly challenging to study as they are dynamic and thus require short acquisition times. Techniques such as Echo Planar Imaging (EPI) and Rapid Acquisition with Relaxation Enhancement (RARE) are fast but not well suited to materials with short relaxation times. Fast Low Angle Shot (FLASH) is a gradient echo technique and can be used for rapid imaging of relatively short T_2 material, however, it is heavily T_2^* weighted, which limits the signal to noise ratio achievable [12]. Single Point Imaging (SPI) is a pure phase encode technique that can be implemented with very short dephasing times and is therefore well suited to imaging short T_2 and T_2^* materials. However, relatively long acquisition times are required, even with fast SPI techniques such as SPRITE [9]. Slice selection with pure phase encoding is also a challenge so it is commonly used for three dimensional rather than two dimensional acquisitions, further increasing the acquisition time. Other techniques commonly used for short T_2 and T_2^* materials are sweep imaging with Fourier transformation (SWIFT) [13] and zero echo time (ZTE) [14], however these are also not slice selective. UTE

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potentially provides a method for rapidly imaging heterogeneous material with slice selection.

The acquisition time for UTE images may still be too long for studying evolving systems such as fluidized beds. Recently, CS has been introduced to reduce the acquisition time of MRI experiments by up to an order of magnitude [3,15,16]. CS works by exploiting the natural structure of MR images to reconstruct images accurately from partially sampled k-space data. CS has been applied to many systems [17–21] and pulse sequences but to the authors knowledge, has not yet been used with UTE.

One of the challenges associated with implementing UTE is ensuring that the gradient shape is generated accurately. It is well known that the gradient shape produced by the gradient amplifiers and coil does not match the input gradient perfectly. The error in gradient shape is typically corrected through the gradient pre-emphasis. However, the pre-emphasis may not produce the exact input gradient especially when short ramp times are used as in UTE. In most imaging sequences the remaining error is small enough that it does affect the final image. UTE is sensitive to the shape of the slice selection gradient, therefore it is desirable to ensure the gradient shape is accurate. A recently published technique by Goora et al. [22] introduces the idea of gradient pre-equalization as a technique to correct for the induced errors in gradient shape when using a short ramp. Their approach is applicable on almost any hardware platform and therefore is appealing for UTE imaging applications in material science and chemical engineering.

In this paper, common artifacts associated with the slice selection in UTE are illustrated using simulations of the Bloch equation. Experimental measurements are then used to demonstrate the implementation of accurate slice selection using UTE. In order to ensure accurate slice selection, the shape of the slice selection gradient was optimized by introducing the gradient pre-equalization of Goora et al. [22]. To reduce the acquisition time without introducing artifacts CS is used for image reconstruction. The UTE sequence is developed using a sample of doped water and the potential of UTE is demonstrated using samples of cork and rubber that have short T_2^* and T_2.

2. Background of UTE

UTE uses a soft excitation pulse, typically of a half Gaussian shape, to minimize the echo time (TE) [23]. Slice selection is achieved by applying a gradient at the same time as the soft pulse. When using a full Gaussian pulse, a second gradient is used to refocus the spins that have dephased during the second half of the radiofrequency (r.f.) pulse. This gradient must have the same area, but opposite sign, as that used during the second half of the r.f. pulse. Therefore, the refocusing gradient is typically of half the duration of the r.f. pulse. The duration of the refocusing gradient limits the minimum TE for slice selective excitations. The minimum TE for the sequence would occur if the acquisition were to begin immediately after the negative gradient lobe typically corresponding to around 0.5 ms or more. UTE overcomes this limitation by using the half shape which is formed by truncating the full shape at the zero phase point [24]. As the excitation ends at the zero phase point, the refocusing gradient is not needed and the acquisition can begin as soon as the r.f. pulse ends. However, as the excitation is truncated it gives a dispersion excitation, that is an excitation with both real and imaginary terms. To eliminate the imaginary component of the excitation the sequence needs to be executed twice. The two acquisitions are identical except that the slice select gradient has opposite sign. The sum of these two acquisitions produces an identical slice to that produced by a full Gaussian and refocusing gradient as the imaginary signals, i.e. the dispersion peaks, cancel and the real signals, i.e. the absorption peaks, add [24].

A half Gaussian excitation requires the slice gradient to be switched off at the same time as the r.f. pulse ends. In practice it is impossible to switch off a gradient immediately owing to limitations in the slew rate that can be achieved by the gradient hardware. It is therefore necessary to switch the gradient off relatively slowly using a ramp. However, as the gradient strength decreases the instantaneous, apparent slice thickness of the r.f. pulse increases. Variable Rate Selective Excitation (VERSE) [25,26] is used to reshape the r.f. pulse to account for the time varying strength of the slice gradient. The VERSE pulse is designed such that the real-space bandwidth of the pulse remains constant as the gradient is decreased. A constant bandwidth is achieved by decreasing the power of the r.f. pulse, whilst increasing its duration and keeping the total applied power constant. This allows for the r.f. and gradient pulses to be switched off simultaneously.

In order to minimize T_2^* weighting, acquisition in a UTE sequence starts as soon as possible after the slice gradient switches off, typically about 10–50 μs is required to allow for ring down of the coil. As the acquisition starts immediately, a center out, non-Cartesian, sampling of k-space is required as there is no time for a phase encode gradient or de-phasing read gradient [24]. Typically k-space is sampled radially however, spiral sampling has also been used for samples with a somewhat longer signal lifetime [6]. A center out sampling pattern is desirable as it minimizes the echo time and ensures maximum signal sampled at the center of k-space. A drawback of non-Cartesian sampling is that it prevents the use of the fast Fourier transform (FFT), and therefore image reconstruction becomes prohibitively time consuming for many images. To overcome this limitation, "re-gridding" techniques have been developed to interpolate the measured signal onto a regular Cartesian grid which can then be transformed using the FFT [27]. It is important to choose the convolution function for this interpolation process accurately. Theoretically, a sinc function of infinite extent should be used, however, this is not practical. Common alternative convolution functions include truncated sinc interpolation, Kaiser–Bessel interpolation and min–max interpolation [28,29]. Such re-gridding techniques permit image reconstruction in almost the same time as with Cartesian sampling.

Non-Cartesian sampling, especially radial sampling, acquires data non-uniformly throughout k-space. In the case of radial sampling, many more points are acquired at the center of k-space (i.e. in the low spatial frequency region). If all data points are weighted equally, the Fourier transform would be biased to these low frequency data resulting in a low spatial resolution, or heavily blurred, image. Density compensation is used to overcome this limitation [30]. Density compensation considers the sampling density throughout k-space and uses a weighting function to correct for this. For radial sampling the weighting function will increase the contribution of the points around the edge of k-space prior to re-gridding and Fourier transformation.

Re-gridding with density compensation alone can produce blurring and artifacts in the reconstructed image, especially if the number of lines in the radial sampling pattern is small. An alternative approach is to iteratively reconstruct the image based on the a priori assumption that the unknown spin proton density image is sparse with respect to a specific representation. This assumption results in nonlinear optimization methods such as CS [3,16–19].

3. Methods

All experiments were performed using a Bruker, AV400 spectrometer, operating at a ^{1}H resonance frequency of 400.23 MHz. A three-axis, shielded gradient system with a maximum strength