Sensitivity Encoding of Chemical Shifts

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INTRODUCTION

The chemical shift artifact (CSA) results from temporally undersampling a spatial-spectral distribution along a tilted k-t trajectory. This is illustrated in Fig. 1 for the case of ^{1}H imaging. Figure 1(a) shows a typical ^{1}H spatial-spectral distribution, in which the two predominant spectral components are from lipid and water protons. Figure 1(b) shows the k-t space sampling pattern typical of a spin-echo echo-planar imaging (SE-EPI) sequence. The CSA artifact (Fig. 1(c)) resulting from direct Fourier reconstruction of these samples can be understood using the projection-slice theorem.

Techniques for resolving different spectral components (e.g., Dixon methods, chemical shift imaging, and echo-planar spectroscopic imaging) typically use more than one temporal encoding, which increases the duration of an experiment. We propose a method that uses a single temporal encoding, but is still capable of correcting the CSA and resolving the different chemical species.

THEORY AND METHODS

We model the spectral-spatial distribution of interest as the combination of L different images, where each image corresponds to a distinct spectral component. Due to the off-resonance effects outlined in Fig. 1, each spectral component will see a slightly different Fourier imaging operator, and the acquired data can be modeled as Eq. 1 plus noise, where the ρ_ℓ are the different spectral images, and the $\mathbf{F}_\ell$ are the corresponding Fourier operators. Using standard spatial encoding without additional temporal encoding, there is insufficient information to separately recover the different spectroscopic images. This changes, however, with the addition of an array of receiver coils. With M coils, data can now be modeled as Eq. 2, where the $\mathbf{S}_m$ matrices include the effects of the coil sensitivity profiles. With $M > L$ and for a sufficient number of spatial encodings, this matrix equation can be inverted, resulting in the set of different spectroscopic images. This resolution of different spectral components is a slight modification of SENSE [1], and is analogous to k-t SENSE [2] or PARADISE [3].

Figure 1. Chemical shift artifact is the result of temporal undersampling.

Equation 1:
$$\mathbf{d} = \sum \mathbf{F}_\ell \boldsymbol{\rho}_\ell$$

Equation 2:
$$\begin{bmatrix} \mathbf{d}_1 \\ \vdots \\ \mathbf{d}_M \end{bmatrix} = \begin{bmatrix} \mathbf{F}_1\mathbf{S}_1 & \cdots & \mathbf{F}_L\mathbf{S}_1 \\ \vdots & \ddots & \vdots \\ \mathbf{F}_1\mathbf{S}_M & \cdots & \mathbf{F}_L\mathbf{S}_M \end{bmatrix} \begin{bmatrix} \boldsymbol{\rho}_1 \\ \vdots \\ \boldsymbol{\rho}_L \end{bmatrix}$$

RESULTS

Figure 2 shows the performance of the proposed algorithm in the context of a diffusion weighted (b=1 000 s/mm^2) twice-refocused SE-EPI experiment conducted on a human brain, using a Siemens Allegra 3T scanner with a phased array of M=4 receiver coils. All experiments were performed in accordance with the local institutional review board. Figure 2(a) shows the sum-of-squares image resulting from standard Fourier reconstruction of the EPI data; the extracranial lipid signal has shifted by roughly 20% of the field of view due to the temporal spacing between different phase-encoding lines. Figure 2(b) shows images reconstructed using the proposed technique (L=2). Reconstructions were performed using a spatial-spectral version of iterative non-Cartesian SENSE [1], using a Toeplitz matrix formulation [4] to improve computational speed. As can be seen, the method can correctly separate the two predominant spectral components. However, significant noise perturbations and residual aliasing artifacts are present, which are due to the poor-conditioning of the parallel imaging equations and inaccuracies in the estimated coil sensitivity profiles. The conditioning in this particular case is worse than for conventional SENSE reconstruction, due to the spatial smoothness of the coil sensitivities and the relatively small shift between the water and fat signals. Incorporating additional prior information does improve reconstruction quality. For example, Fig. 2(c) shows reconstructions for a case in which we've provided additional region-of-support information and moderate regularization. However, artifacts have not been completely eliminated.
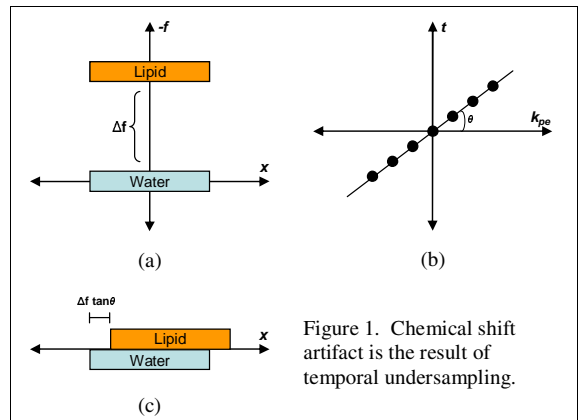

(a) Standard reconstruction   (b) Reconstructed water (left) and lipid (right) images   (c) Reconstructed water(left) and lipid (right) images using region-of-support information
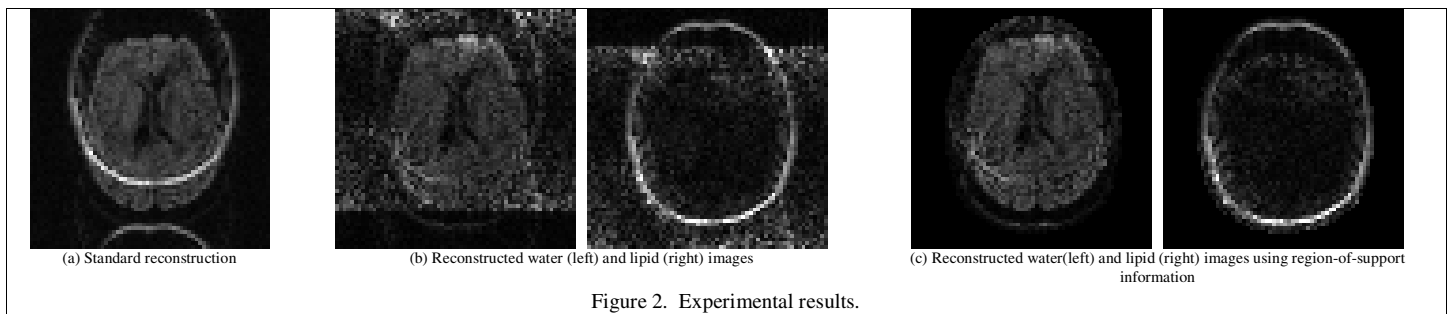
Figure 2. Experimental results.

A number of possibilities exist for improving these results; for example, the k-t space trajectory can be optimized and/or augmented to afford the best possible conditioning for the spectral separation problem. However, even with trajectory optimizations, the proposed technique will have greater noise sensitivity relative to more standard spectroscopic imaging sequences that rely on more complete coverage of k-t space. This sensitivity can be described in terms of a geometry-factor, analogous to the one defined for standard SENSE [1].

CONCLUSION

We have proposed a new spectroscopic imaging technique in which conventional temporal encoding is replaced by sensitivity encoding of the chemical shift artifact. This enables the separation of different chemical species using standard single-shot imaging sequences. However, the noise penalty incurred by using sensitivity encoding is a significant limitation of this approach.

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