Generalized *k*-Space Decomposition for Non-Cartesian Water/Fat Imaging

E. K. Brodsky[1,2], J. H. Holmes[2], H. Yu[3], and S. B. Reeder[1,2]

[1]Radiology, University of Wisconsin - Madison, Madison, WI, United States, [2]Medical Physics, University of Wisconsin - Madison, Madison, WI, United States, [3]Global Applied Science Lab, GE Healthcare, Menlo Park, CA, United States

INTRODUCTION

Blurring caused by chemical shift of off-resonant spins has limited the combination of non-Cartesian acquisitions with chemical shift based imaging methods, especially at lower receiver bandwidths and with long readout durations. For this reason, chemical shift methods such as "Dixon" imaging have been mostly limited to spin-warp acquisitions where the bulk shift of fat in the readout direction ("chemical shift artifact") is well-understood and clinically acceptable. For non-Cartesian sequences, however, the phase roll accumulated by off-resonant spins is far more destructive to image quality. IDEAL [1,2] is a multipoint chemical shift based water/fat decomposition technique that provides uniform separation of water and fat in the presence of B_0 inhomogeneities using three or more complex images acquired at arbitrary echo spacing. The purpose of this work is to develop a generalized *k*-space based chemical shift decomposition method using the IDEAL representation that eliminates blurring by accounting for the phase evolution throughout the *k*-space trajectory. This enables robust fat separation with non-Cartesian sequences, without the need for spatial-spectral pulses, short readouts, or high bandwidth imaging. While chemical shift correction techniques have been described in the image domain [3,4], the *k*-space-domain approach introduced here is unique in that it can fully correct the phase roll at each *k*-space point.

THEORY

The IDEAL signal model relates the complex signal of a voxel with its water and fat content, based on echo time and species' chemical shifts. Historically, separation has been performed in the image domain, treating each echo as having been acquired instantaneously at the time the center of *k*-space was sampled. However, this assumption does not account for phase roll accrued through *k*-space across each individual echo. This phase accrual and the associated blurring can be eliminated by instead performing IDEAL in *k*-space. The signal $s_n(\tau_{\mathbf{k},n}, \mathbf{k})$ at *k*-space point $\mathbf{k}$ sampled in echo *n* at time $t_n + \tau_{\mathbf{k},n}$ is described by the following equations:

$$s_n(\tau_{\mathbf{k},n}, \mathbf{k}) = \sum_{m=1}^{M} \rho_m e^{i2\pi\Delta f_m (t_n + \tau_{\mathbf{k},n})} = \sum_{m=1}^{M} \rho_m c_{mn} d_{mn}(\mathbf{k})$$

$$c_{mn} = e^{i2\pi\Delta f_m t_n}, \quad d_{mn} = e^{i2\pi\Delta f_m \tau_{\mathbf{k},n}} \qquad \text{[Equation 1]}$$

where ρ_m and Δf_m represents the signal and chemical shift, respectively, of species *m*. The sample time is represented as the sum of two components: t_n, the time the center of *k*-space was acquired for echo *n* (i.e. the nominal echo time); and $\tau_{\mathbf{k},n}$, the relative time between acquiring sample point $\mathbf{k}$ and the center of *k*-space. Taking the pseudo-inverse of this signal model applied to multiple echoes yields a maximum likelihood estimate of ρ_m based on the acquired signal s_n. The c_{mn} term has been described previously and is a fixed component based only on echo time and species chemical shift. The new $d_{mn}(\mathbf{k})$ term describes the phase evolution for each species across an echo and is described by $\tau_{\mathbf{k},n}$ and species chemical shift.

MATERIALS AND METHODS

The *k*-space water/fat separation method was tested on a human knee with a GE Healthcare 1.5T scanner using a 2D spiral acquisition (Figure 1a) with an 8192 sample (33 ms) readout, 16 arms, ±125kHz bandwidth, and nominal echo times of 4.4/6.0/7.5 ms. The acquired dataset was processed using a regridding algorithm to generate complex images as well as the "acquisition time" map, $\tau(k_x, k_y)$, representing the delay within an echo between sampling each point in *k*-space and sampling the origin (Figure 1b). The complex echo images were processed using the IDEAL algorithm to yield a smoothed field inhomogeneity map, $\psi(x, y)$, which was used to demodulate phase shifts in the complex echo images. The complex echo images were then transformed back to *k*-space using an inverse FFT, and decomposed into water and deblurred fat *k*-space images using the pseudo-inverse of Equation 1. A final FFT yielded the corrected water and fat images, which were summed to give an in-phase combined image.

RESULTS

As seen in Figure 1, the uncorrected phase of off-resonant spins leads to severe blurring of the fat signal, with the *k*-space chemical shift method leading to substantial reductions in this artifact. In addition to the spiral trial, the technique was also tested with similar success (results not shown) for radial (using half-echo and full-echo readouts) and conventional Cartesian spin-warp imaging.

DISCUSSION AND CONCLUSION

K-space chemical shift decomposition allows non-Cartesian imaging of water and fat without using spectrally-sensitive excitation. The improvements are especially significant for imaging techniques involving long readouts, which were previously not clinically feasible without the use of fat suppression. Coupled with the optimal echo combination achievable with IDEAL, this approach may enable a new class of efficient and robust non-Cartesian water/fat imaging acquisitions that were not previously possible due to chemical shift artifacts.

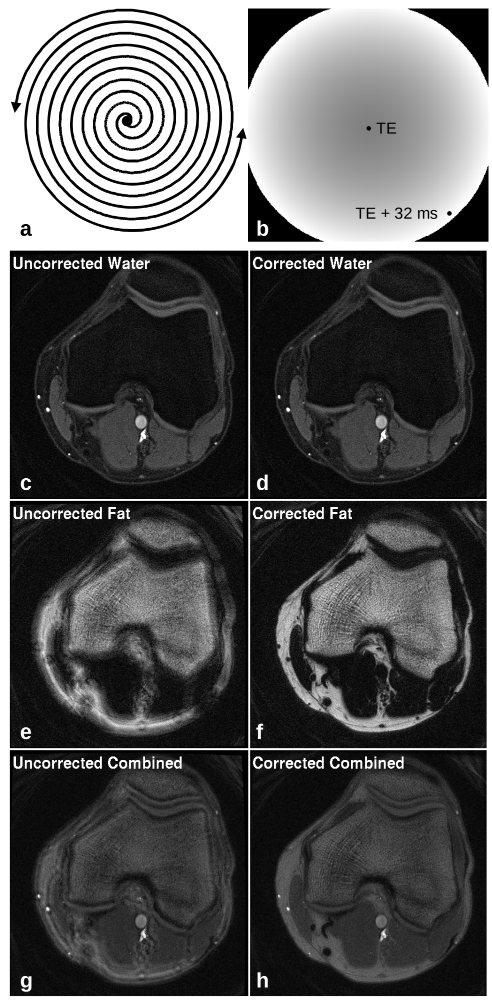

***Figure 1**: Spiral imaging is very sensitive to chemical-shift artifacts due to the phase evolution of fat during its long readouts. Fat signal is severely blurred, obliterating detail of subcutaneous fat and trabecular bone structure (e) and obscuring nearby anatomy (g). K-space IDEAL provides substantial improvement in image quality (f, h) without the need for spectral-spatial water excitation pulses.*

REFERENCES AND ACKNOWLEDGEMENTS

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