IDEAL Water-Fat Decomposition with Multipeak Fat Spectrum Modeling

H. Yu[1], A. Shimakawa[1], C. A. McKenzie[2], J. H. Brittain[3], and S. B. Reeder[4]

[1]Global MR Applied Science Lab, GE Healthcare, Menlo Park, CA, United States, [2]Department of Medical Biophysics, University of Western Ontario, London, ON, Canada, [3]Global MR Applied Science Lab, GE Healthcare, Madison, WI, United States, [4]Departments of Radiology, Medical Physics, Biomedical Engineering and Medicine, University of Wisconsin, Madison, WI, United States

Introduction Multi-point water-fat separation methods typically acquire images at two or more echo times such that the phase shifts between water and fat can be exploited to form separate water and fat images [1-5]. Previous multi-echo methods use a relatively simple signal model that assumes that both water and fat have a single resonant frequency separated by 3.5ppm. For most applications this is a satisfactory model and excellent qualitative water-fat separation can be achieved. However, it is well known that fat has a number of spectral peaks [6], as shown in Figure 1. These side peaks result in a baseline level of signal within adipose tissue on the separated water images. For example, peak 3 is close to the water resonant frequency, and water-fat separation methods typically place its signal in the water image. The incomplete suppression of fat in the water image may reduce the desired contrast between the water tissue and the surrounding fatty tissues. In addition, there has been growing interest in the use of chemical shift based methods for quantification of fat in organs such as the liver. For such quantitative applications, the side peaks of the fat spectrum must be considered. In this work, we describe an improved method for separation of water and fat by modeling a more accurate fat spectrum that consists of multiple peaks. We combine this model with the Iterative Decomposition of water and fat with Echo Asymmetry and Least-squares estimation (IDEAL) [5], referred to as Multipeak IDEAL (MP-IDEAL). Furthermore, a spectrum self-calibration algorithm is introduced to estimate the fat spectrum directly from the 3-echo source data. We demonstrate that greatly improved fat suppression can be achieved with better conspicuity between non-fatty tissues and the adjacent adipose tissue.

Methods For the MP-IDEAL model, we can write the signal from a voxel containing a mixture of water and fat as: $s(t) = \left(\rho_w + \rho_f \sum_{p=1}^{P} \alpha_p \cdot e^{j2\pi \Delta f_p t}\right) \cdot e^{j2\pi \psi t}$, where Δf_p and α_p are the resonant frequency (relative to water) and the relative amplitude of the p^{th} fat peak (p=1, …, P), respectively, with $\Sigma\alpha_p$=1. If the fat spectrum is known (Δf_p and α_p), water, fat and the Bo inhomogeneity map (ψ) can be estimated by using the conventional IDEAL algorithm [5] modified to replace the single exponential fat-associated signal weighting ($e^{j2\pi \Delta f_1 t}$) with a weighted sum of exponentials ($\sum \alpha_p \cdot e^{j2\pi \Delta f_p t}$).

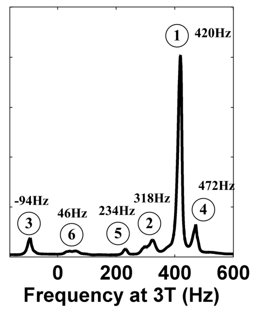


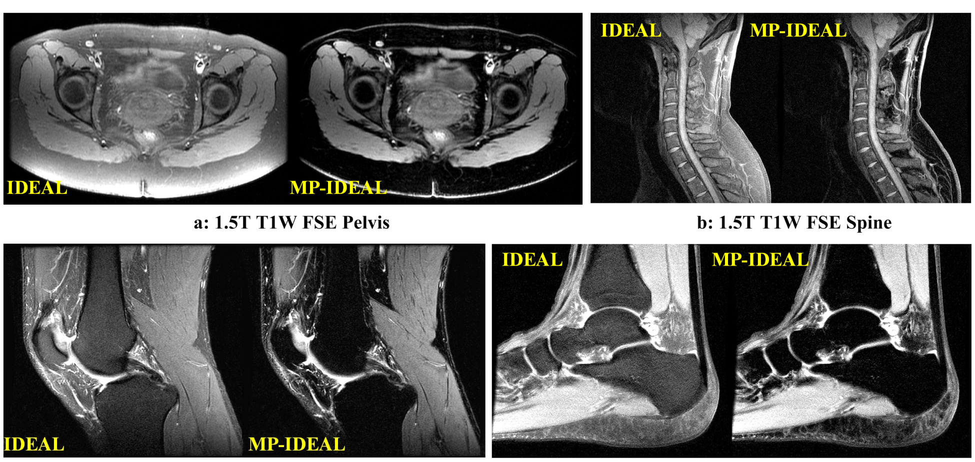
Figure 1: A fat spectrum acquired in a phantom containing peanut oil. Chemical shift frequencies at 3T are labeled relative to the water resonant frequency (0Hz) and in the order of relevance to this work (see text).

The values of Δf_p are known to be relatively constant, so they are considered known and the values labeled in Figure 1 are used. Because α_p may change slightly from scan to scan, as a result of differences in relaxation parameters between peaks, it is directly estimated from the 3pt data. Due to the limited temporal sampling with the 3-pt data, we only estimate the relative amplitudes of the 3 primary peaks in the fat spectrum (peak 1-3 in Figure 1). Peak 4 also has appreciable signal; however it is very close to peak 1, so the phase evolution between the two peaks is small (~π/6) with the 3-pt IDEAL echo times. Peaks 5 and 6 are small, and thus can be ignored. We first perform a conventional 3-pt IDEAL reconstruction, from which the pure fat pixels are automatically selected for the spectrum calibration and their fieldmap values are obtained. The identification of fat pixels can be achieved in an automatic fashion by comparing the water and fat contents in a pixel. At these fat pixels, the field map is demodulated from acquired signals. The relative amplitudes can thus be estimated independently at these pixels using a linear least squares inverse by treating the signal intensities at the 3 peaks as three independent species. Finally, α_p estimated at these fat pixels are averaged to obtain the final relative amplitudes. In practice, this spectrum self-calibration processing is performed at the center slice of a dataset and the calibrated α_p are used at all slices.

Phantom, volunteer and patient scans were performed on GE 1.5T TwinSpeed and 3.0T VH/i (HDx, GE Healthcare, Waukesha, WI) scanners with informed consent and permission from our Institutional Review Board (IRB) for all human scanning. Images were collected using a fast spin-echo (FSE) sequence and a 3D spoiled gradient echo (SPGR) sequence modified for use with the IDEAL method. The echo times optimized for conventional 3-pt IDEAL were used [7].

Results Results from over 100 datasets were obtained in a variety of clinical applications to demonstrate the improved water-fat decomposition using the MP-IDEAL, including knee, ankle, breast, spine, brachial plexus, pelvis and abdomen. Representative results from four scans are shown in Figure 2. While conventional IDEAL achieves uniform water-fat separation, residual fat signal in the water images is evident as a result of the fat side peaks. Fat is better suppressed in the MP-IDEAL water images, where cartilage is better depicted (in knee and ankle) and the contrast between the muscle and the surrounding fatty tissues is greatly improved. For a given dataset, fat appears uniformly dark at all slices from MP-IDEAL, supporting the assumption that the fat pixels within the same dataset can be characterized by the same spectrum. The excellent results also suggest that the spectrum self-calibration algorithm provides sufficiently accurate estimates of α_p.

Discussion and Conclusion We have modified the signal model for the IDEAL water-fat separation method, in order to create a more accurate representation of the fat signal evolution. Our results demonstrate great improvement in image quality with decreased fat signal in the water images. The signal model used in MP-IDEAL requires accurate knowledge of the fat spectrum. With the spectrum self-calibration method, MP-IDEAL's sensitivity to potential spectrum variation is reduced and no additional scanning is required. The self-calibration method assumes that all fat pixels in the dataset follow the same signal behavior. One limitation is that it doesn't take into consideration the possible intra-data spectrum variation in different disease states or fatty tissues, although this effect has not been observed from our experiments. Nonetheless, the modified multipeak model is more representative of the true fat spectrum than the previous single peak model. In conclusion, MP-IDEAL provides greatly improved fat suppression, which may have useful applications for fat quantification.



a: 1.5T T1W FSE Pelvis **b: 1.5T T1W FSE Spine**

c: 3T T2W FSE Knee **d: 3T T2W FSE Ankle**

Figure 2: Representative results from four in-vivo scans. Water images from conventional IDEAL and MP-IDEAL are shown.

References

[1]. Dixon et al, Radiology 1984;153(1):189-194.
[2]. Glover et al, MRM 1991;18:371-383.
[3]. Xiang et al, JMRI 1997;7:1002-1015.
[4]. Ma et al, MRM 2004;52:415-419.
[5]. Reeder et al. MRM. 2004; 51:35-45.
[6]. Thomsen et al, MRI 1994 12 487-495
[7]. Pineda et al. MRM. 2005;54:625-635.