Gradient Reversal Technique Revisited for Simultaneous Water and Fat Imaging at High Field

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Introduction Qualitative and quantitative MR imaging of water and fat is of great importance in obesity and diabetic research, osteoarthritis cartilage visualization, body composition measurement, and drug evaluation studies. In these applications, accurate assessment of tissue lipid levels as well as fat or water content distribution, in modified small animal models, is critical. At very high field, the available spectral selection or saturation techniques are often hampered by severe susceptibility artifacts; and the spatial-spectral selective excitation techniques [1] are limited in practice by their requirement for high gradient amplitude and switching rate during the short RF pulse train. The alternative Dixon method [2] may not be desired for applications at very high field because the chemical shift during slice selective excitation causes a severe mis-registration of water and fat slices. Besides, Dixon method requires multiple data acquisitions. In this study, we revisited the gradient reversal technique [3], along with a chemical-shift-specific slice-selection (C4S) method [4]. Simultaneous water and fat imaging approach was implemented at 11.7T. Using this technique, high quality water and fat images at the identical slice locations were acquired in a single acquisition without increase in acquisition time. Applications in *in vivo* quantitative tissue lipid imaging were demonstrated.

Methods

Gradient reversal technique for water and fat imaging within single acquisition During slice selection, water and fat slices could be completely offset in the slice direction when $\Delta\omega_{rf} < \Delta\omega_{off}$, where $\Delta\omega_{rf}$ is the RF bandwidth of excitation pulse, and $\Delta\omega_{off}$ is the frequency offset between water and fat resonances. The gradient reversal technique [4] and C4S [5] involve the application of a slice selective 90° pulse, followed by a refocusing 180° pulse with reversed slice selection gradient. As shown in Figure 1, if the RF pulses were at resonance for a water slice, only the water slice will be excited for spin echo because it experiences both 90° and 180°. Repeating this schedule with RF frequency on fat resonance will allow fat from the same slice refocused and excited. Figure 1 also illustrates the scheme to image both water (W) and fat (F) slice in a single acquisition without scan time increase. The scheme can be extended to multi-slice fat and water imaging provided that slice interval (center-to-center) frequency is $\geq \Delta\omega_{off} + \Delta\omega_{rf}$ to avoid partial inversion of the fat or water signal during 180° pulse excitation. This technique is generally applicable to the 2D and 3D sequences that involve refocusing RF pulses. It is especially suited for high field applications, whereas at low field the requirement of $\Delta\omega_{rf} < \Delta\omega_{off}$ leads to long RF pulse duration and restricts its practical applications.

Imaging experiments All imaging experiments were performed on a Bruker Biospin 500WB spectrometer (Bruker NMR, Inc., Billerica, MA) with an 89 mm vertical bore magnet of 11.7 T and a shielded gradient system up to 100 G/cm. For quantitative water and fat imaging, interleaved water and fat selective spin echo sequence capable of multi-echo and multi-slice acquisition was implemented using the gradient reversal and C4S techniques, with excitation frequency bandwidth $\Delta\omega_{rf}$ 1750Hz (3.5ppm at 11.7T), TR sufficiently long, and TE the shortest, to minimize T1 relaxation effect. Optimized Gaussian-shaped slice selective RF pulses were chosen for the imaging sequence. The multi-echo images were fitted to mono-exponential decay to remove the T2 effect, and the water and fat proton density (PD) images were generated pixel by pixel, from which the lipid percentage maps could be obtained for in vivo lipid quantification and distribution in mice.

All animal experiments were approved by the Institutional Animal Care and Use Committee. *In vivo* lipid measurements in mouse liver and hind limb muscle were done using wild-type lean mice and the obese mice that are on high fat diet for 5 months. The mice were anesthetized with 1.5% isoflurane/O2 gas mixture delivered through a nose cone. During the liver imaging, mice were positioned in a 30mm ID RF coil. Six interleaved water and fat selective images at three slices locations were acquired with respiratory gating (per slice triggering), resulting in a TR about 6s. Spoilers at both sides of the reversal gradient were optimized, and descending aorta flow saturation was used, to minimize flow artifacts. Other parameters were TE = 4.5 ms, number of echoes = 8, FOV = 30 mm, acquisition matrix = 168 × 168, thickness = 1.5 mm, and number of averages = 2. In the present muscle lipid study, a 10mm ID RF coil was used for optimum sensitivity. Image SNR was optimized to overcome the challenge of low lipid content and heterogeneous distribution. High resolution water and fat images were acquired from the left hind limbs, with TR/TE = 2s/4.5ms, number of echoes = 8, FOV = 12.8 mm, acquisition matrix = 128 × 128, thickness = 1 mm, and number of averages = 32.

Results Fig. 2 shows fat (a) and water (b) images of phantom acquired simultaneously using the gradient reversal technique. Fig. 2c is the chemical-shift-artifacts free image derived from the summation of Fig. 2a and 2b acquired in a single acquisition. Fig. 2d is the conventional spin echo image containing both in-plane and through-plane chemical-shift effects. Fig. 3 demonstrates the *in vivo* water (a) and fat (b) images (PD weighted, TE = 4.5ms) of the obese liver. Fig. 1(c) and 1(d) show the color-coded liver lipid percentage maps of the obese and lean mice respectively. About 30% lipid was detected in the obese liver, whereas about 8% lipid was in the lean liver. Fig. 4 shows the high resolution *in vivo* cross sectional water and fat images and the lipid percentage map in hind limb muscle of the obese and lean mice. The subcutaneous and inter-muscular fat regions were not included in the muscle lipid percentage map. On average, 50% more lipid was detected in the obese limb.

Conclusions and discussions The gradient reversal technique for chemical shift selective imaging was revisited for applications at very high field. A simultaneous water and fat imaging sequence with in-plane chemical-shift correction was successfully implemented at 11.7T to assess lipid content and distribution in liver and hind limb muscle of mice *in vivo*. The quantitative nature of the results indicates that this method has good sensitivity and can be applicable to longitudinal studies of lipid modifying therapies. Compared to the DIXON method, this technique can image both water and fat from the identical slice location and does not require multiple acquisitions. At very high field, this water and fat imaging approach is simple to implement, robust, and quantitative.

Reference 1. Schick F. Magn Reson Med 1998; 40:194–202. 2. Dixon WT. Radiology 1984; 153:189-194. 3. Park HW, Kim DJ, Cho ZH. Magn Reson Med 1987; 4:526-536. 4. Volk A, Tiffon B, et al. J Magn Reson 1987; 71:168-174.

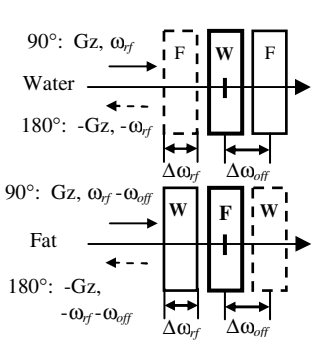

Fig.1. Scheme to excite both water and fat slices in a single spin echo acquisition. Horizontal axis is the slice location selected.

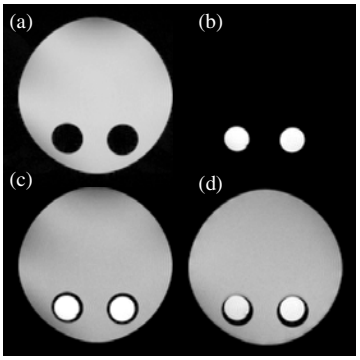

Fig.2. Water and fat phantom images at 11.7 T. (a) fat image (olive oil); (b) water image; (c) fat plus water image; (d) conventional spin echo image.

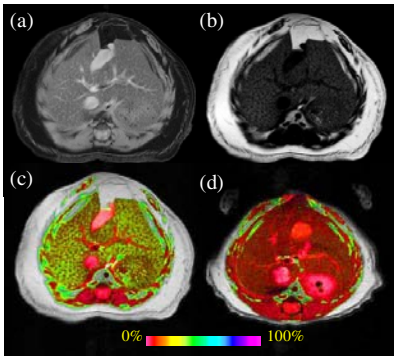

Figure 3

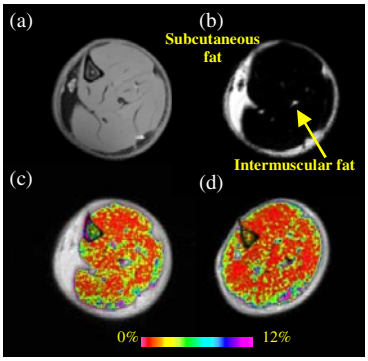

Figure 4

Figs. 3 & 4. In vivo water and fat images and lipid quantification in mouse liver and hind limb. (a) water image; (b) fat image; (c) color coded lipid percentage map of an obese mouse; (d) lipid percentage map of a lean mouse.