Homogeneous Water-Lipid Phantoms with Matched T1 and T2 Relaxation Times for Quantitative Magnetic Resonance Imaging of Tissue Composition at 3.0 Tesla

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Introduction: The differential excitation, suppression, or separation of water and lipid signals has been useful for clinical and research applications. Quantitative MRI and spectroscopic (MRS) techniques could benefit from the use of phantoms which would serve as calibration standards for the water and lipid composition. A technique is presented for the fabrication of stable, homogeneous phantoms over the full range of relative water-to-lipid fractions. The approach is both simple and inexpensive to implement. The phantoms have the same T_1 and T_2 values for both the water and lipid components to eliminate the systematic error in the calculation of water-to-lipid fractions caused by use of finite parameters such as TE and TR. The MRI measured water fractions (W_f) are compared with those determined by weight.

Methods: Lard was used as the lipid compound of choice because it approximated the spectral widths and peaks observed in-vivo better than vegetable compounds. Lecithin (Sunrise Health Products, Brookfield, CT) was chosen as an inexpensive and accessible emulsifying agent and added directly to the melted lard at 2% by weight. The mixture was continually heated and stirred until completely dissolved. Low melting point agarose (A9414 Agarose, SIGMA-Aldrich Corp., St. Louis, MO) and distilled water were used to create the water component of the phantoms. 0.6 mM of Gd-DTPA (Berlex Labs, Wayne, NJ) in water was heated to boiling and a 2% fraction of agarose powder by weight of water was slowly added while continuously stirring. Once mixed, the temperature of the water-agarose mixture was reduced to 70 ^{o}C. The desired quantity of lipid-lecithin mixture by weight added to the water-agarose gel while quickly stirring to achieve the desired percent water fraction. The combined mixture was removed from the stirrer when almost set, poured into a 30 ml vial and allowed to cool to room temperature.

All MR image data were acquired on a 3.0 Tesla GE MRI scanner (GE Medical Systems, Milwaukee, WI) using a transmit/receive head coil. Water fractions were obtained using a 3-point Dixon (3PD) acquisition. 3PD acquisition parameters were a TE = 17 ms, TR = 4000 ms, a 256 x 128 matrix, a 24 cm FOV and a 10 mm thick slice. T_2 measurements were performed using a multi-echo 3PD acquisition with echo times of 17, 34, 51, and 68 ms. T_1 values were estimated using a single echo 3PD acquisition and repetition times of: 100, 250, 500, 750, 1000, 1500, 2000 and 4000 ms. Relaxation times and water fractions were verified using a single voxel STEAM spectroscopy sequence. Data were acquired with TR = 4000 ms, TE = 17 ms, 2048 data points and a sweep width of 5000 Hz. As the signal-to-noise ratios were typically of order 100:1 per excitation, only a single excitation was acquired. The 3PD data were transferred to a PC for computation of W_f using software written in IDL (RSI/Kodak, Boulder, CO). The W_f was calculated on a per voxel basis from the results of the Dixon decomposition as: $W_f(x,y) = W(x,y) / (W(x,y) + \rho F(x,y))$ (Fig 1). The coefficient ρ=1.1 is a correction for the relative mass density of water versus lipid. The phase wraparound problem inherent in producing separate water (W(x,y)) and lipid (F(x,y)) images and image misalignment due to the chemical shift differences were overcome using a previously published iterative algorithm. After ROI's were selected from the W_f images, the mean and standard deviation of the signal intensities were used to assess phantom composition and spatial uniformity. T_1 and T_2 values were extracted from the water and lipid images produced from the 3PD acquisitions. ROI's were chosen on the resulting parametric images to produce histograms of the relaxation values within the region from which the mean of the distribution was extracted using a Gaussian fit. Spectra were transferred to an SGI Octane workstation for analysis using XsOsNMR software (X. Mao, D.C. Shungu). Lipid peaks were identified as: (1-olefinic, C-H=C-H, 5.18 ppm), (2-$(CH_2)'$ 1.93 ppm), (3-methyl, $(CH_2)_n$, 1.15 ppm), (4-methylene, CH_3, 0.76 ppm) (Fig 2). Here $(CH_2)'$ refers to a resonance consisting of several components with CH_2 groups. Frequency domain fitting yielded peak areas which were used for comparison of W_f with those obtained using the 3PD method.

Results: An increase in the dry weight percent of the agarose gel from 1 wt% to 5 wt% was compared with the T_2 values of water and lipid in a phantom containing 50% water and 50% lard by weight. The lipid T_2 was invariant with changes in agarose concentration with a mean value of 28.0 ± 1.6 ms. The water and lipid T_2 curves crossed at an agarose gel concentration of approximately 2 wt% which was used in subsequent phantoms to provide matched T_2 values. The T_1 values of water and lipid in a 2 wt% agarose gel phantom containing 50% water and 50% lard by weight crossed at an approximate concentration of 0.6 mM Gd-DTPA in the 2 wt% agarose gel. No effect on phantom T_2 values for water or lipid was found as a function of Gd-DTPA concentration. The water component of the phantom yielded T_2 = 30.1 ± 4.4 ms, which matched that of the lipid component at 29.8 ± 2.0 ms. A set of water/lipid phantoms was prepared using 0.6 mM Gd-DTPA doped agarose gel at 2.0 wt% with the addition of 2.0 wt% lecithin. Using the 3PD technique, the measured W_f and the W_f by weight displayed a noticeable variance from linear behavior with respect to percentages by weight (Fig 3). This was not observed for the measurements made using magnetic resonance spectroscopy (MRS). The phantoms were determined to be spatially homogeneous in W_f to within 5%. The T_1 values of the water and lipid components were 259.8 ± 23.8 ms vs. 275.0 ± 11.0 ms. Water T_2 values (30.7 ± 3.4 ms, n=10) were also reasonably well matched to those of the lipid (26.3 ± 1.7 ms, n=10) although there was some spatial variation across samples.

Discussion: Gd-DTPA doping achieved matched T_1 values for the water and lipid components. Similarly, the T_2 value of water in the gel was made comparable to the T_2 of the lipids by varying the agarose concentration. The 3PD approach allows for high resolution images of the water and lipid components.An implicit average over the relaxation times of methylene and methyl resonances, and an average over the olefinic proton of lipid and the water resonances for the water component at lower water concentrations is assumed. However, only two distinct frequencies are easily accounted for in the W_f calculation, while other resonances have a phase that is modulated by a cosine function of resonance offset. MRS does not suffer from this limitation but accounts for individual resonances of Fig 2 provided an independent check on the accuracy of the 3PD method. The deviation from linear behavior for 3PD in Fig 3 can be explained by calculating the W_f using all resonances observed in the spectroscopic measurement as $W_f = W / (W + \rho[O + (CH_2)' + (CH_2)_n + CH_3])$, where the lipid component has been resolved into olefinic (O), $(CH_2)'$, $(CH_2)_n$ and CH_3 resonances. A linear relationship was obtained versus measurement by weight with R^2 = 0.99. However calculation of the W_f using only the water and $(CH_2)_n$ resonance yielded a curve that was in close agreement with 3PD method. A method has been presented for the construction of water-lipid phantoms for MRI and MRS with matched T_1 and T_2 relaxation times. The phantoms described herein are stable, homogeneous, and span the entire range of water-to-lipid ratios.

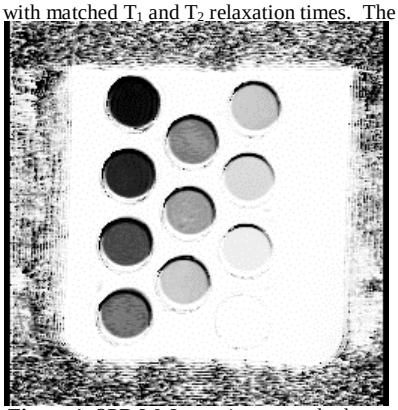

Figure 1: 3PD W_f Image in a water bath

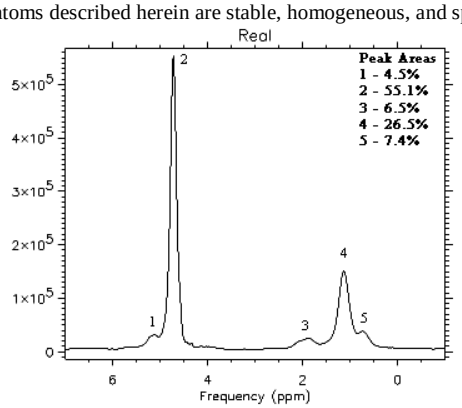

Figure 2: 50% W_f Spectrum

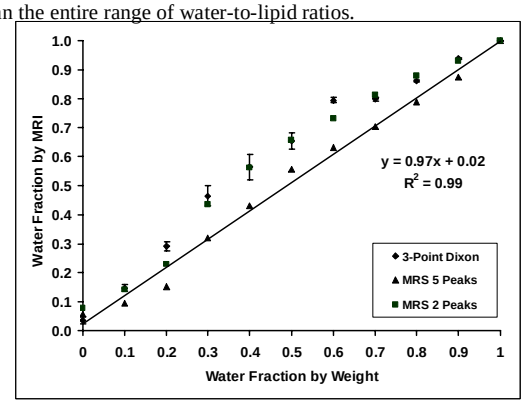

Figure 3: MRI/MRS W_f vs. W_f by Weight

1) Hilaire L, Wehrli FW, Song HK. Magn Reson Imaging 2000;18:777-786, 2) Glover GH, Schneider E. Magn Reson Med 1991;18:371-383.