Separating Fat and Water

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Introduction: The ability to separate fat and water signal is significant advantage in MRI compared to other diagnostic modalities. As fat signal is often not of diagnostic interest, this task is often reduced to simply suppressing the unwanted fat signal. However, increasing interest in the effects of obesity, the ability to provide negative contrast with breast lesions, and certain musculoskeletal applications provide advantage to imaging fat and water signal separately and simultaneously.

Suppression of fat based on its T1 relaxation time – The first methods used to suppress fat signal centered on its relatively short T1 relaxation rate relative to other tissues. An inversion recovery preparatory pulse is used to invert all magnetization prior to imaging. The interval between the inversion pulse and the imaging sequence is chosen such that fat signal is nulled when imaging begins. The inversion time necessary is *ln(2) * T1(fat)*. The method is often referred to as Short Tau Inversion Recovery (STIR).

In spin echo sequences, the inversion preparation is played prior to every imaging excitation. Relative to methods based on the chemical shift between fat and water signal, fat suppression with STIR is superb as fat suppression is not dependent on B_0 homogeneity. Additional care with STIR sequences, namely adiabatic RF inversion pulses, can make fat suppression less sensitive to B_1 homogeneity. However the inversion pulse imparts a significant deleterious effect on signal levels and limits the types of image contrast possible. Though these problems are serious, they can be somewhat mitigated with additional imaging sequences to provide other mechanisms at providing the wanted contrast and signal.

In gradient recalled echo imaging sequences, the cost of imaging time for STIR can be quite significant. Often then, more than one line of k-space is acquired per preparation pulse. Thus, fat signal is not nulled completely for each area of k-space. When using Cartesian trajectories, the ordering of phase-encoding is chosen such that lines near the center of k-space are acquired at the point when fat signal is nulled. One such method is known as SPECIAL(1). When using non-Cartesian sequences, filtering can be performed to preferentially weight signal acquired at the fat null point. As the number of lines of k-space per inversion pulse is increased, imaging speed increases while the quality of fat suppression decreases.

At field strengths below 0.7T, STIR becomes the increasingly prevalent method to suppress fat signal. STIR methods At field strengths at or above 0.7T, the frequency offset between fat and water provides an increasingly attractive method to suppress or separate fat signal.

Suppression of fat signal based on its chemical shift- Fat signal is generally considered to have a 3.3-3.5 ppm chemical shift relative to water signal. Carbon-hydrogen bonds in fat create a cloud of charge that produces an induced magnetic field which opposes the applied static B_0 field. The field is beginning to appreciate that fat signal is actually a combination of several distinct frequency offsets, due to multiple carbon – hydrogen bonds in lipids (C-H2, CH3, CH=CH)(2).

The dominant clinical method for suppressing uses a spectrally selective RF preparatory pulse to tip fat into the transverse plane and dephase it prior to imaging. The method is known often simply as *fatsat or chemsat*. Designing a RF pulse to excite fat while leaving water unaffected becomes easier at higher field strengths as the separation between fat and water grows. Thus *fatsat* pulses become shorter at higher field strengths. The time required for *fatsat* pulses creates a similar cost on imaging time as described for STIR above. The cost in imaging time is relatively minimal for spin echo sequences but significant with gradient-recalled sequences. Thus, gradient recalled sequences using fatsat preparation often image several lines of k-space and take care to order k-space to maximize fat suppression and minimize artifacts.

Fatsat methods are sensitive to both B_1 and B_0 inhomogeneity. B_1 inhomogeneity causes only partial excitation of the unwanted fat signal. As low levels of B_0 inhomogeneity, unwanted fat signal shifts away from the passband of the *fatsat* pulse and is only partially excited. At larger levels of B_0 inhomogeneity, the desired water signal can actually shift into the passband of the *fatsat* pulse and be inadvertently dephased. A strong primer for designing RF pulses for fatsat methods is provided in Bernstein's Handbook of MRI Pulse Sequences (3)

CHEmically Shift Selective (CHESS) (4) pulse sequence methods aim to spectrally select all spins within the desired spectral band. As these methods provide no spatial selectivity, these methods must either be applied to 3D imaging or utilize another selective pulse, such as a 2D spin reversal pulse, to provide spatial selectivity.

Multiple dimension pulses- Two and three dimensional spatial excitation can be performed by using gradient waveforms to traverse excitation k-space while depositing RF energy. By considering that the analog of the time required for excitation maps out a spectral dimension, RF pulses can be designed to have both spatial and spectral selectivity. Such pulses are referred to as spectral-spatial pulses (5).

Spectral-spatial excitation is often used to selectively excite only water spins without perturbing fat magnetization. The method is not sensitive to B_1 inhomogeneity, as the objective is not to excite and dephase fat signal as in the fatsat method. The method is less sensitive to B_0 inhomogeneity, as much larger B0 shifts are required before lipid signal is inadvertently excited. A more likely problem is for the desired water signal to shift out of the desired spectral passband and fail to be excited. Like fatsat methods, the pulse must be long enough to design an effectively sharp passband to avoid inadvertent fat excitation. Thus these pulses are generally easier to design at higher field strengths. As these pulses use oscillating gradients, greater care and effort is required to properly provide the real-time frequency modulation required to select slices away from isocenter.

Fat/Water Separation

Dixon-based Methods - The first prevalent methods to separate fat and water signal utilized linear combinations of two separate acquisitions. In one acquisition, an echo time is selected such that fat and water signal are in phase. In another, the echo time is selected such that fat and water are out of phase. In the absence of B_0 inhomogeneity, the addition of such signals produces a water image while the subtraction produces a fat image. These initial methods are referred to as 2-point Dixon (CITE). A thorough discussion of Dixon's original methods and Dixon-based methods is found in Section 17.3 of Bernstein's Handbook of MRI sequences(3)

When viewed as a linear combination, the Dixon method can be viewed as a solution to a system of equations to solve for the amount of water and fat signal present in each voxel. In regions where B_0 inhomogeneity is significant, conventional 2-point Dixon can't separate fat and water as the effects of B_0 inhomogeneity mimic chemical shift. In these cases, more sophisticated methods are needed.

Glover and Schneider(6) devised a 3 point Dixon method which used an additional measurement at another echo time to resolve B_0 inhomogeneity, fat signal and water signal. Since then, several new methods have been added to improve the ability to separate fat and water using Dixon-based methods. These methods allow improved robustness in regions of strong B_0 inhomogeneity. Many publications have built upon this work to solve problems where the B_0 field map is rapidly changing. By utilizing information from the surrounding area instead of considering each voxel independently, more robust performance can be achieved. A good discussion of these methods is provided in Section 17.3.3 of Bernstein's Handbook (3). One popular method described by Ma provides an alternatives to the scan time increase imposed by the redundant data collection in 3 point Dixon method(7). Here only a reference scan and additional echo time are used. Both the amplitude and phase of surrounding pixels are used to separate the effects of fat, water, and B_0 inhomogeneity.

In IDEAL (Iterative Decomposition of water and fat with Echo Asymmetry and Least squares estimation)(8), signal from multiple acquisitions (typically three) are fitted to a signal model which accounts for water, fat, and B0 inhomogeneity effects. A field map is first generated using an iterative least-square estimation approach. The effects of B0 inhomogeneity can then be removed (demodulated) prior to solving a system of now linear equations for the amounts of fat and water present in each pixel. The IDEAL method can be expanded to model the effect on signal when lipid is viewed properly as a multiple peak spectrum. Accurate fat quantification can be provided if confounding factors such as T1-bias, eddy current induced phase errors, and T2* are accounted for (2). Quantifying the degree of fat infiltration in the liver, where fat is believed to be a precursor to serious liver disease in some individuals, is a growing application of fat quantification.

Steady-state methods of fat/water separation - When the increased gradient performance of scanners allowed the true-FISP (FIESTA, fully balanced SSFP) sequences to deliver high signal levels on vendor platforms approximately ten years ago, the inherently large lipid signal in true-FISP was a deleterious feature of such methods. While one learns quickly how the spectral notches in true-FISP create possible banding artifacts, several researchers have developed methods to exploit the spectral selectivity of true-FISP to either suppress an unwanted species or separate fat and water simultaneously.

In fat-suppressed steady-state free precession (FS-SSFP), one periodically interrupt the steady-state and saturate fat spins (9). Water selective balanced steady-state free precession (WS-bSSFP) is another method to eliminates fat signal (10) though it extends the TR and thus increases sensitivity to B_0 inhomogeneity. Phase sensitive fat/water detection exploit the near binary phase profile in the SSFP response, but has difficulties with partial voluming of fat and water (8,11). Fluctuating equilibrium magnetic resonance (FEMR) and linear combination steady-state free precession (LC-SSFP) sequences have demonstrated the ability to separate fat and water spins without a loss in SNR efficiency, though they are constrained by short TRs which limit the time available for spatial encoding (12-13).

Over the past years, methods have been created to alternate TRs of different lengths to create fat nulls for fully balanced SSFP sequences while allowing adequate time for spatial encoding. One such example is fat-suppressed ATR(14), which uses two different alternating length TRs with a TR2:TR1 ratio of 1:3 and RF phase cycling to shape the spectral frequency response to place a stopband over the fat resonance.

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