A Short-train SSFP Sequence with Instrinsic Fat Suppression

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Introduction: The FISP sequence employs steady-state free precession (SSFP) to provide a high signal-to-noise ratio (SNR) that is practically independent of the sequence repetition time (TR). Unfortunately, the TRs commonly employed in FISP generate large signals from fat that, due to chemical shift, are phase opposed to those of water-based tissues causing destructive interference. Fat also causes problems in FISP sequences employing a short echo planar type readouts where the combination of large signals and chemical shift generates ghosting artifacts. Existing methods to suppress fat signals include spectrally selective RF saturation and inversion-recovery nulling of fat prior to imaging. Both these methods have drawbacks: they are slow, necessitate a lengthy interruption of the FISP steady state and the fat signal recovers during the subsequence imaging process. The Linear-Combination SSFP [1] method provides spectrally selective imaging, but requires the acquisition of two or more phase cycled images to separate fat from water. We now propose a SSFP imaging method that provides intrinsic spectral selectivity, suppressing a wide band of signals throughout the FISP imaging process. Here, this spectral selectivity is exploited to provide water selection and fat suppression, although the following discussion may be generalized to provide alternate spectral separations where required.

Theory: The idealized SSFP sequence generates echo signals at approximately TR/2 between RF pulses [2]. These echoes differ from conventional spin-echoes: they may have both positively and negatively phased spectral components. Isochromats that precess an approximately even number of cycles during TR yield echoes in-phase with on-resonance isochromats, and vice-versa, providing the opportunity to partition isochromats into two well-defined spectral components. Since fat has a chemical shift of 3.3ppm (210Hz at 1.5T), a SSFP sequence with 2.4<TR<7.1ms generates echoes with fat in anti-phase to water. To effect separation, the FISP sequence is broken into short SSFP-trains comprising, for example, 8-64 RF pulses. Between the SSFP-trains, the water isochromats are z-stored. Residual transverse magnetization, comprising spins that were phased opposed to the on-resonance water, are then gradient crushed and RF spoiled by changing the scanner exciter and receiver phase. The stored magnetization is subsequently re-excited using the linearly ramped opening sequence method [3] with very little disturbance to the steady-state water signal. The additional time required to play the sequence is 1-2 TRs and so does not greatly affect imaging efficiency. To effect greater suppression the flip angle may also be ramped up to 90º just prior to the end of the SSFP-train as shown in Figure 1. Simplistically, considering each SSFP-train as a sequence unit, the effect on fat is similar to a conventional gradient- and RF-spoiled sequence. For water, there is no spoiling and the sequence retains the SSFP qualities of FISP.

Methods: Simulations were performed to obtain the steady-state signal response as a function of off-resonance frequency, and to compare the performance of (1) a standard SSFP sequence and a short SSFP-train sequence with (2a) gradient crushing only applied between trains; and (2b) both gradient crushing and RF spoiling. Adjustable parameters for simulation included flip-angle, TR of the SSFP sequence, the SSFP-train length, the number of TRs to be used for the opening and closing ramp sub-sequences and whether to use RF spoiling between successive SSFP-trains. The T1/T2 tissue relaxation parameters used were: myocardial muscle: 880/80ms; and fat: 250/80ms.

Experiments were performed using a 1.5T GE Signa CV/i MRI scanner (GE Medical Systems, Waukesha, WI). An imaging sequence was developed for (a) conventional FISP imaging and (b) the short SSFP-train method with optional RF-spoiling and opening and closing sub-sequences as described in the theory section. Images were obtained from oil/water phantoms and from human volunteers. In all cases, the center frequency was adjusted to ensure that the water and fat peaks were placed symmetrically with respect to the SSFP-transition band at 1/(2TR) below the scanner center frequency, with the water peak approximately on resonance in the pass band and the fat peak in the stop band. Images were obtained with (1) a standard FISP acquisition with sufficient dummy TRs to ensure that a true SSFP condition applied, and with the short-train SSFP sequence using (2a) only gradient spoiling between the SSFP-trains and (2b) gradient and RF spoiling.

Results: Figure 2 shows the simulated magnetization response as a function of off-resonance frequency for fat and muscle tissue to (1) a conventional SSFP sequence; and a 24-TR SSFP train based sequence with (2a) gradient spoiling, and (2b) gradient and RF spoiling. Figure 3 shows a comparison of images obtained using conventional FISP sequence and the short-train SSFP sequence. Images were acquired in the human calf, and a short axis swine heart.

Discussion: A simple modification to the FISP imaging sequence that provides an efficient means of fat-suppression has been developed. The method avoids interrupting the SSFP steady state for a lengthy period while an explicit fat-saturation sequence is played out. The length of the SSFP-train is an important parameter for the method. In practice, the actual duration of the train is of greater importance than the particular length of the train in terms of number of TRs: the train should be short enough for gradient and RF-spoiling to be effective, and yet long enough for the fat/water isochromats to become properly phase opposed. The method works well with continuous imaging methods. When image datasets are to be acquired using multiple SSFP-trains, the phase-encoding steps can be interleaved between SSFP-trains, permitting view-shared imaging in which the reconstruction frame rate exceeds the true acquisition frame rate. The method should work well in combination with magnetization preparation methods (e.g. IR perfusion). Chemical shift increases linearly with field strength, giving a fat/water separation of approximately 420Hz at 3T, so that fat and water will be phase-opposed for 1.2<TR<3.6ms and 5.9<TR<8.3ms.

References: [1] S.S Vasanawala et al. MRM:43:82-90:2000. [2] K. Scheffler MRM 49:395-397:2003 [3] J. Hennig et al. MRM 48:801-809:2002.

Figure 1

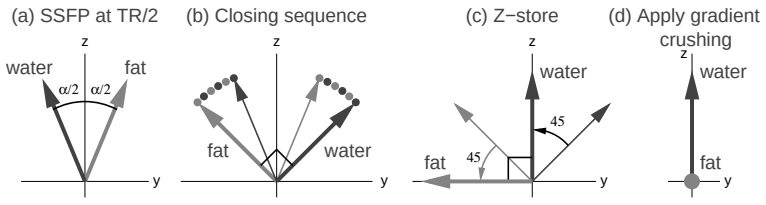

Figure 2

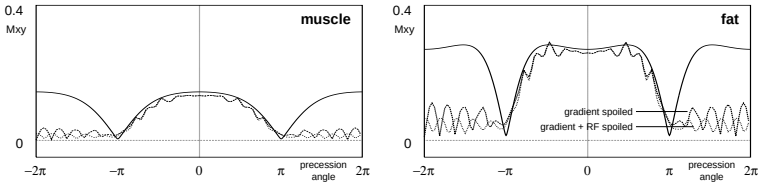

Figure 3