An Approach to True Water-Fat Separation by Phase-Cycled SSFP and Single Quadrature Dixon

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Synopsis

This work presents a data processing algorithm for water-fat separation using phase-cycled SSFP and the single quadrature Dixon (SQD) method. By using a combinatory SSFP signal, the new algorithm is capable of mapping the inhomogeneity phase free of any interference from the chemical-shift phase. Therefore, it provides the ability of achieving true water-fat separation using the SQD method in combination with phase-cycled SSFP.

Introduction

Though SSFP provides great signal-to-noise performance and desirable image contrast, its application has been hindered by the existence of band artifacts and strong fat signal. Phase-cycled or frequency-shifted SSFP have been shown to be efficient ways for removing the banding artifacts [1]. Recently, the SQD method has been combined with phase-cycled SSFP for water-fat separation [2]. However, in its original implementation, the inhomogeneity phase map is estimated from SSFP sub-signal in which the water and fat signals are orthogonal in phase. With such an orthogonal phase arrangement, the effects on phase from field inhomogeneity and chemical-shift cannot be truly separated without knowing the exact water-fat composition of each voxel. Consequently, true water-fat separation cannot be achieved for voxels consisting of both water and fat.

Theory

Phase-cycled SSFP signals can be combined to yield multiple sub-signals of different echo-formation pathways [1], e.g. S_{-1}, S_0, S_1, etc. In SQD phase-cycled SSFP with $TR = 2TE = 1/(2\Delta f)$, where Δf is the frequency separation between the water and fat signals, we can obtain: $S_0 = (W_0 + iF_0)e^{i\phi}$, $S_{-1} = (W_{-1} - iF_{-1})e^{-i\phi}$, $S_1 = (W_1 - iF_1)e^{i3\phi}$, etc., ignoring spin relaxation. Unfortunately, inhomogeneity phase ϕ cannot be determined individually from these sub-signals without knowing the water-fat composition. A combinatory signal, S_0S_1, however, has its phase dominated by inhomogeneity effect: $S_0S_1 = [(W_0W_1 + F_0F_1) + i(F_0W_1 - W_0F_1)]e^{i4\phi}$, since it is mostly true that $|F_0W_1 - W_0F_1| << |W_0W_1 + F_0F_1|$. Therefore, inhomogeneity phase map can be determined using this combinatory signal according to: $\phi = unwrap\{\arg(S_0S_1)\}/4$, where unwrap{} stands for the process of phase-unwrapping and arg[] returns the principle phase value of its complex input. S_0 and S_{-1} images can then be phase-corrected to yield $I_0 = W_0 + iF_0$ and $I_{-1} = W_{-1} - iF_{-1}$. Water and fat images can finally be constructed from the real or imaginary parts of I_0, I_{-1} or both.

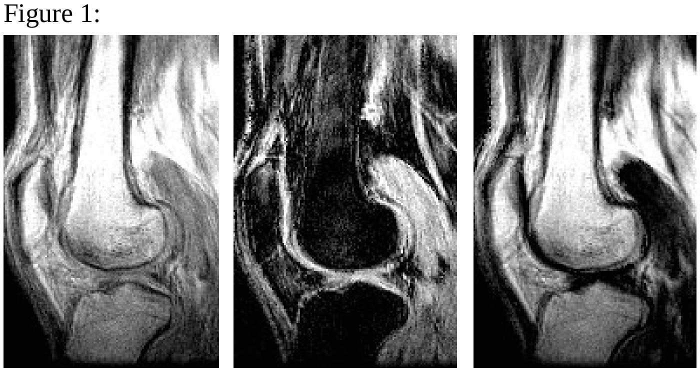
Methods and Procedures

A 3D SSFP imaging sequence with TE=5 ms and TR=10 ms was used and a volunteer knee imaged on an ULTRA scanner (Toshiba Medical Systems Co., Japan) operating at 0.35 T. A six-step phase-cycling scheme was used with the phase of the RF pulses incremented by 0, 60, 120, 180, 240, and 300 degrees, respectively. Signals were combined to yield S_0, S_{-1} and S_1. The separated signals were further processed as previously described to yield water and fat images.

Results

Figure 1 shows SSFP image (left), separated water image (middle) and fat image (right) of a volunteer knee, produced by the currently described method.

Figure 1:



References

[1] Zur Y et al., Magn. Reson. Med. 16:444-459 (1990).
[2] Miyoshi M et al., Proc 11th ISMRM, 981 (2003).