Field-encoded SSFP: A new method for positive-contrast visualization of paramagnetic agents

W. R. Overall[1], and J. M. Pauly[1]

[1]Electrical Engineering, Stanford University, Stanford, CA, United States

Introduction: Positive-contrast techniques for visualizing paramagnetic markers (e.g., SPIO agents) are desirable because of their well-localized signal and insensitivity to partial-volume effects. Current techniques can be grouped into two categories based upon their method of identifying magnetic particles: those exploiting the local gradients induced by the particle [1], and those that use frequency shifts [2-4]. Each technique makes tradeoffs between imaging efficiency, SNR, and robust background suppression. We have developed an SSFP-based positive-contrast technique that combines the inherent scan efficiency of SSFP with simultaneous marker signal selection based on both frequency and local gradient fields. Simulations and experimental validation confirm that the SSFP technique improves SNR efficiency over other methods while retaining effective background suppression.

Methods: Fig. 1(a) shows a 2D histogram of the resonant frequency and local field gradient experienced by spins near a paramagnetic particle. Frequency shifts (Fig. 1(b)) and local gradients (Fig. 1(c)) are both near zero far from the particle and increase with proximity to it. To achieve positive contrast, signal far from the particle should be suppressed. Spectrally selective techniques, including spin-echo techniques [2] and IRON [3], excite off-resonant spins without gradient selectivity (the green box in Fig. 1(a)). Conversely, the gradient-selective 'white-marker' technique [1] selects a range of locally induced gradients irrespective of center frequency (the blue box in Fig. 1(a)) by applying a global compensation gradient prior to readout. We propose an SSFP-based positive-contrast technique that is simultaneously selective on both of these axes, as depicted by the yellow boxes. The technique maximizes desired signal by selecting signal from all four quadrants, and minimizes background leakage by rejecting all spins that are either on-resonant or have no local gradient.

We propose a Field-encoded SSFP (Fe-SSFP) pulse sequence (Fig. 2), which differs from a standard SSFP scan in both its RF pulse and its equal and opposite 'rephasing gradients' before and after readout. These gradients may be located on any axis as long as their area is sufficient to produce more than one cycle of phase across that voxel dimension. This dephases spins in image regions with no local gradient; however, it rephases signal in areas with an equal or opposite local gradient. Specifically, if a local region has a Z gradient arising from the magnetic marker of magnitude $-L$ G/cm (persisting throughout TR), the first rephasing gradient (with area L·TE G/cm·s) exactly cancels the local gradient at the echo time TE=TR/2, and a coherent echo forms. The local gradient field adds to the post-readout rephasing gradient, and together effectively forms a gradient spoiler of area -2·L·TE. Hence, for some range of negative-Z local field gradients, the net effective sequence acts as a gradient-spoiled (GRE) experiment. Alternatively, a $+L$ G/cm local Z gradient adds with the rephasing gradient prior to readout while exactly cancelling the post-readout rephasing gradient. This arrangement (effectively, a spoiler prior to readout and none afterward) acts as a CE-FAST pulse sequence, and coherent signal is again present at TE. Thus, rephasing gradients suppress signal in regions distant from the marker and rephase signal near the marker based on its local gradient magnitude, regardless of sign. This differs from the white-marker technique, which rephases local gradients of only one polarity.

To further suppress background signal, the Fe-SSFP sequence also employs a 5-ms minimum-phase SLR RF pulse with dual spectral passbands of width 1000 Hz centered at ±650 Hz. Because the desired signal arises from GRE and CE-FAST signal pathways, TR can be somewhat longer than in typical SSFP imaging. Sequence parameters were: TR=9.5 ms, TE=4.7 ms, 16-cm FOV, and a 256^2 matrix. Projection images shown here were acquired in less than 3 seconds; we have also used this technique for 3D scans. For slice-selective imaging, one could forego spectral selectivity at some cost to background suppression.

Results: Fig. 3 shows experimentally acquired Fe-SSFP signal as compared with signal from a white-marker sequence with similar parameters. Signal magnitudes are similar in each case, but Fe-SSFP has approximately twice the volume of coherent signal because it is sensitive to positive and negative local gradients simultaneously. When spectrally selective RF is used without rephasing gradients (Fig. 4(a)), signal suppression is incomplete due to an imperfect shim. Similarly, when rephasing gradients alone are used (4(b)), high-spatial-frequency edges are incompletely suppressed. When both are used (4(c)), good suppression is achieved.

Discussion: We have demonstrated a new positive-contrast susceptibility imaging method using refocused SSFP. SNR efficiency is comparable to that of existing methods, and good background suppression is achieved through two redundant methods. Signal can be obtained from closer to the marker by appropriate changes in RF bandwidth and rephaser-gradient area.

References: [1]. Seppenwoolde, JH, *et al.* MRM 50(4): 784-790, 2003. [2]. Cunningham, CH, *et al.* MRM 53(5): 999-1005, 2005. [3]. Shah, SS, *et al.* Proc. 14th ISMRM: 3499, 2006. [4]. Reeder, SB, *et al.* Proc. 14th ISMRM: 430, 2006.

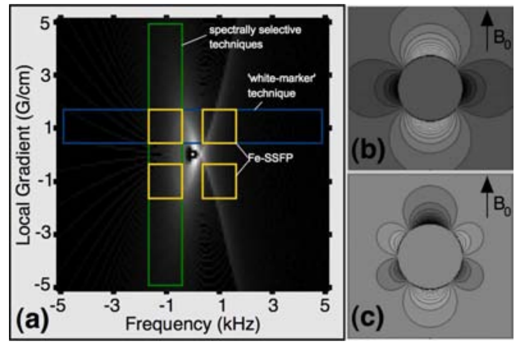

Figure 1. *(a): 2D histogram of field behavior near a paramagnetic marker. Spins closer to the marker have larger off-resonant frequency (as in (b)) and/or local gradient (as in (c)). Positive-contrast methods exploit these effects to generate contrast.*

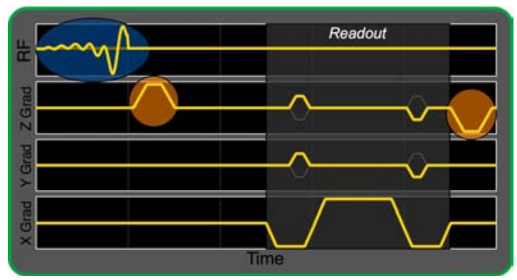

Figure 2. *Fe-SSFP pulse sequence. A spectrally selective RF pulse (blue oval) suppresses on-resonant signal. Rephasing gradients (orange circles) counteract the local gradient present near the dipole marker and spoil background signal.*

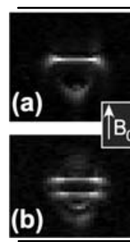

Figure 3. *White-marker (a) and Fe-SSFP (b) signal from a paramagnetic marker. White-marker signal occurs at positive local gradients, while Fe-SSFP signal arises from both positive and negative local gradients (compare with Fig. 1(c)). Gradient rephasers are oriented along B_0.*

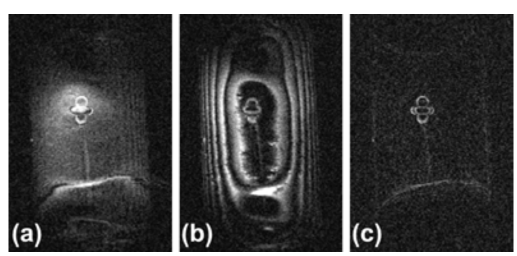

Figure 4. *Fe-SSFP without rephasing gradients (a) and without spectral RF selection (b) each suffer from inadequate background suppression. When both are used (c), suppression is enhanced.*