Stimulus Induced Rotary Saturation (SIRS); a new method for the direct detection of neuronal currents with MRI

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INTRODUCTION   Neuronal currents produce transient and oscillatory magnetic fields at frequencies (<100 Hz) that can be readily detected by MEG. The source of these fields are thought to be small current dipoles (<100 nAm) composed of synchronous intracellular postsynaptic currents of parallel pyramidal cells in the cortical mantle and a diffuse current return path. Previous work attempting to detect these magnetic fields with MR has focused on local phase shifts and dephasing effects in T2 or T2* weighted images [1,2]. One potential problem with this method is the detection of bipolar, or "zero mean" temporal waveforms often seen in MEG. Unless the bipolar current pulse is carefully timed around a refocusing pulse in a spin echo experiment, the phase shift induced by the positive and negative episodes of the neuronal current will cancel each other.

Recently ultra-low field MRI has been proposed to allow resonant interaction between the neuronal currents and spin magnetization [3]. Here the B0 field is lowered to produce a Larmor frequency of less than 100Hz and the transient neuronal magnetic fields act as resonant "excitation" pulses providing the initial tip of the proton magnetization. In this case a bipolar or oscillatory "zero mean" neuronal current is actually beneficial as long as its spectrum contains power at the Larmor frequency (which is <100Hz). In this work we present an alternative resonant method with similar advantages but which can be used with high field MRI. We utilize spin-locking to sensitize the spins to neuronal magnetic fields oscillating at the Larmor frequency in the rotating frame (γB_{1lock} between 20 and 100Hz). Oscillating neuronal currents with spectral power at $\omega = \gamma B_{1lock}$ are capable of producing rotary saturation of the spin-locked magnetization. Thus the neuronal currents produce a resonant saturation effect on the MR signal in the rotating frame during the spin-lock state. The resonant frequency in the rotating frame during spin lock can be set to approximately match the expected neuronal current oscillations by adjusting the B_{1lock} amplitude. In analogy with the classic rotary saturation experiment of Redfield [3], we refer to this method as Stimulus Induced Rotary Saturation (SIRS). We demonstrate in phantom experiments that the method is capable of detecting local dipole currents of a similar magnitude to that observed by MEG without significant signal averaging (~100nAm).

METHODS   All measurements shown here were performed at 3T (Trio, SIEMENS Medical Solutions, Erlangen, Germany). A 2mm copper wire current dipole of 1 cm length (Fig. 1) was placed 5.4 cm deep in a 17 cm diameter saline (0.9% NaCl) filled sphere and connected to a digital frequency synthesizer (Global Specialties 2003). The phantom was aligned so that the dipole was perpendicular to the B0 field. In order to measure the current through the phantom the voltage across a 1 kΩ series resistor was monitored with an optically isolated differential probe. The synthesizer was gated by the pulse sequence to generate sinusoidal current bursts of a controlled audio frequency during the spin-lock period. The pulse sequence was a spin-lock prepared EPI [5], with a spin-lock duration of TSL=100 ms, 64x64 matrix, 3x3mm voxels, 4mm slice thickness, TE=19ms, TR=1s, BW=2298Hz, θ=90°. A single transverse slice was imaged. A $T_{1\rho}$ = 460ms was measured in the phantom. The spin-lock pulse was implemented to be B_1 compensated or not [5]. To characterize the rotary saturation effect a phantom current of 75μA or 16μA was swept from 20Hz to 80Hz in 1Hz steps, 40 or 160 averages were obtained at each frequency. This experiment was performed with spin-lock fields of γB_{1lock} = 40Hz and 60Hz.

RESULTS   3 voxels directly below the dipole showed a rotary saturation effect (Fig. 2). The slight shift in frequency (2Hz) above the expected resonance is likely due to the Bloch-Siegert shift [6]. The double peak in the 75μA data is likely due to the B_1 compensated spin-lock pulse exhibiting two different amplitudes [5]. There were no phase changes detected in the data. Further, measurements were performed at a current of 16 μA (dipole moment=160nAm) with 160 averages at each frequency and a non-compensated spin-lock pulse (hence only 1 peak). An effect of 0.6% signal magnitude change was observed with an SNR of ~10.
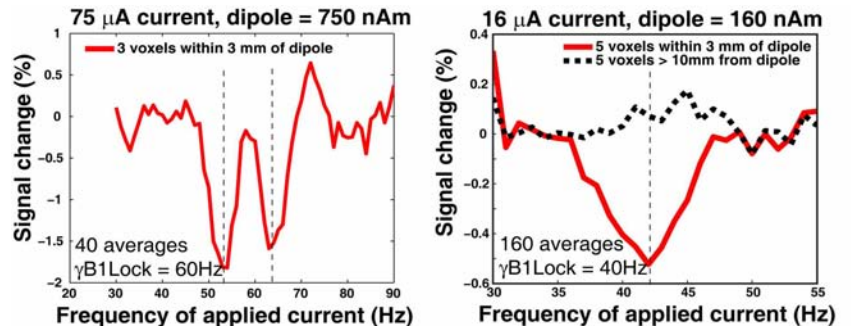

Fig. 2   Image intensity as a function of applied dipole current frequency for a 60Hz and 40Hz spin lock field. Left, dipole = 750nA. Right, dipole = 160nAm.

CONCLUSIONS   Spin-locking can be utilized to create image contrast to magnetic field fluctuations in the frequency range of neuronal magnetic field oscillations. Even at reasonably low current dipole strengths the magnitude change is readily visible after about 100 averages without need for statistical detection. It appears that this approach might ultimately be capable of detecting oscillatory magnetic fields originating from neuronal currents. Furthermore the high frequency specificity allows the design of detection experiments focusing on narrow band oscillations that can be evoked or induced by particular stimuli, making this a potential approach for the localization of oscillatory activity in the brain.

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