Towards direct Neuronal Current Imaging by Resonant Rabi Oscillation Mechanisms

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Abstract: Current approaches aimed at understanding brain function can be broadly divided into those that rely on hemodynamic responses as indicators of neural activity (fMRI, Optical and PET) and methods that measure neural activity directly (MEG and EEG). These approaches all suffer from poor temporal resolution (fMRI), poor spatial localization (MEG and EEG), or indirectly measuring neural activity (fMRI, Optical and PET). It has been suggested that the proton spin population will be altered by neural activity fields resulting in a measurable effect on the NMR signal that can be imaged by MRI methods. Unfortunately, this effect has been determined to be too small to be detectable. We present the physical basis and experimental evidence for an alternative approach based on a resonant interaction between the magnetic fields such as those arising from neural activity, with a spin population that is undergoing Rabi oscillations at a frequency commensurate with the neural currents. It is well established that neural firing during an activation has a spectrum associated with it. For example, multiple unit activity representing large pyramidal cells and some inhibitory activity occur in the frequency range of 400-3KHz. Local field potential which reflect mostly cooperative activity in neural populations are generally thought to extend from 10-90 Hz. Recognizing that neural activity has an inherent spectral content is the key to the approach proposed and validated here. We demonstrate through the use of an ionic current phantom that Rabi induced resonant interactions produce larger changes in the observed NMR signal than those arising out simple spin dephasing[1]. These Rabi interactions may form the basis for imaging neural activity directly with MR with the flexibility for use at conventional clinical field strengths.

Methods: Common to a number of studies of neural current detection with MR is the use of DC current phantoms while human brain activity is likely to have important components of neural activity characterized by waveforms that contain a broad distribution of frequencies. We demonstrate here a method based on Rabi oscillations, which can easily be tailored to the frequency spectrum of the underlying neural activity fields. The required B_1 excitation field is modified according to [1]:

$$\vec{B}_1(t) = \frac{\omega_1}{\gamma}\cos(\omega_1 t)\left[\cos(\omega_{rf}t)\hat{x} - \sin(\omega_{rf}t)\hat{y}\right] \quad \text{with} \quad \omega_1 = \omega' + \pi k t$$

where on resonance, $w_0=w_{rf}$ and with a zero area chirped Rabi pulse as given, represents linearly swept rate of the magnetization oscillation in the yz-plane which is tunable to resonate with the frequencies of the neural activity. The ability to tune the Rabi frequency to the relatively low frequencies of the neural activity fields enables the observation of this unique resonance coupling at any field strength. The use of Rabi oscillation pulses in NMR is new and novel.

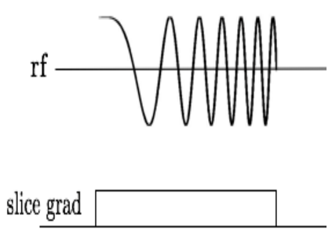

Figure 1

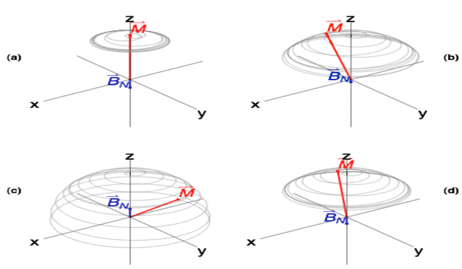

Figure 2

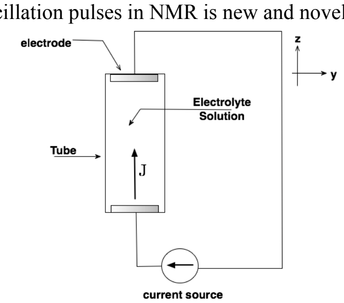

Figure 3

Figure 1: Timing diagram showing the excitation phase of a sequence consisting of a zero area chirped Rabi pulse with a spectral range covering the neural activity dynamics. Figure 2: Bloch sphere simulations showing resonant coupling to simulated neural currents B_N at 120Hz and a Rabi oscillating excitation field at the same frequency. The Rabi frequency is off-resonant with the neural fields by (a) +50 Hz, (b) +20Hz (c) on resonance and (d) -30Hz. The maximum rotation of the magnetization vector thus occurs on when the neural field frequency matches the Rabi oscillation frequency. Figure 3: Schematic of the ionic tube phantom used in the experiments for simulating neuron currents. The electrolyte solution is a saline (0.9 g/100 ml NaCl) doped with 4 mM $CuSO_4$ to reduce T1 time to about 340 ms.

Results:

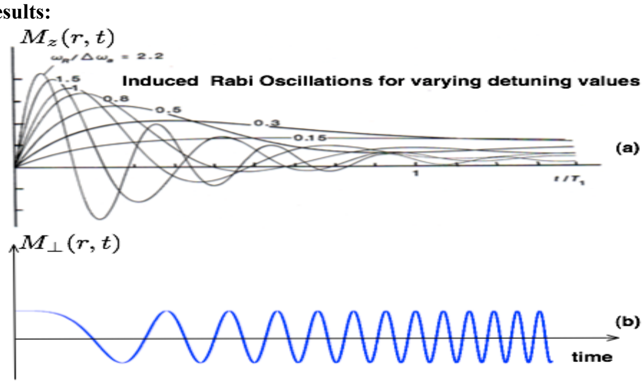

Figure 4: Exact solutions for induced longitudinal magnetization (polarization) for different Rabi detuning parameters. This behavior changes over from weak-signal to strong signal or Rabi flopping behavior for small detuning. This off-resonance detuning can be exploited to produce components of Rabi oscillations that spectral overlap with neural activity (DC to 3kHz) thus enabling the resonant amplification of their respective fields.

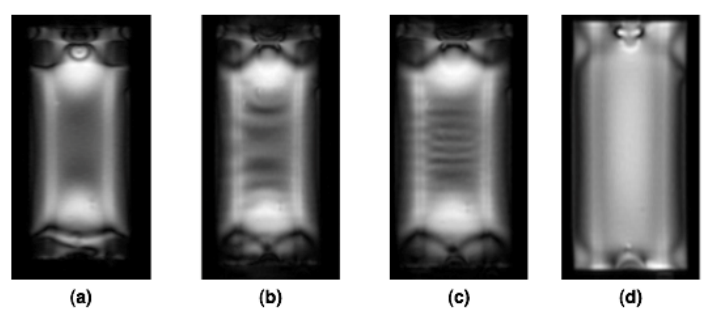

Figure 5: Experimental results showing imaging with the modified excitation with no current flowing through the phantom (a), with a current at 100 Hz (b) and at 200 Hz (c). Note that the fringe spacing is proportional to the frequency of the ionic current. In each case, the frequency of the Rabi pulse was tuned to resonate with the frequency of the ionic current. As a means of comparison, a conventional gradient echo sequence was used to image the phantom at the same ionic current frequency of 100 Hz with the result as shown in (d). Note the absence of fringe patterns in this case indicating the sequence inability to detect these small fields. The susceptibility distortions at either end are due to the copper electrode interface.

Conclusions: We have, analytically, experimentally and through simulations, demonstrated the detection of the resonant interaction between magnetic spins made to oscillate from ground state and back to excited states through Rabi oscillations with fields such as those due to neural activity. We have achieved this in an ionic current phantom with equivalent amplitudes of 10-100 nAm, approximately representative of human evoked brain activity. This is a significant milestone as the Rabi frequency can be tuned to any range within the spectrum of neural activity. We are currently in the process of applying this technique to human subjects using evoked response protocols that elicit neural activity in specific frequency bands that can be tuned to the Rabi oscillation of the excitation field.

References: [1] A Kiruluta, JMR 182:308-314 (2007).