Spin-locked Oscillatory Excitation (SLOE): Towards *in-vivo* Detection of Oscillating Neuronal Currents

Jingwei Sheng[1], Yuhui Chai[1], Bing Wu[2], Weinan Tang[1], and Jia-Hong Gao[1]
[1]*Center for MRI Research, Peking University, Beijing, Beijing, China,* [2]*GE Healthcare MR Research China, Beijing, China*

Purpose: To push towards *in-vivo* detection of brain oscillating neuronal currents with a novel MRI method.

Introduction: Detection of neuronal currents using MRI has fundamental impacts on brain functional studies, and the neuronal currents are mostly likely to be oscillatory waveforms with a frequency distribution rather than direct current (DC). Hence the phase shift induced by both positive and negative episodes of neuronal currents is likely to cancel out. Stimulus-induced Resonant Saturation (SIRS) was proposed to exploit this fact, and detected an oscillatory magnetic field of about 1 nanotesla (nT) in dipole phantom [1]. However, the *in-vivo* neuronal magnetic field caused by evoked or spontaneous activities was only estimated to be in the sub-nT which might cause failure to the SIRS method at 3T. Most recently, a new method has been proposed by our group based on spin-lock technique [2] and we named it Spin-locked Oscillatory Excitation (SLOE). In this work, we demonstrate the superiority of SLOE over SIRS method through quantitative comparison in a phantom study. Furthermore, the sensitivity in detecting sub-nT oscillatory fields applied on anesthetic rats was also verified and hence makes *in-vivo* detection of neuronal currents feasible.

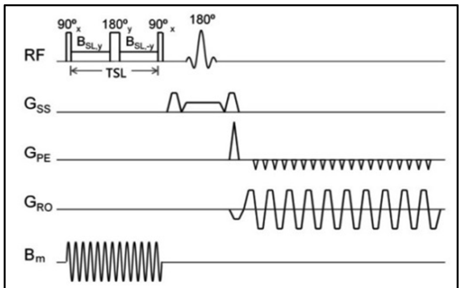

Figure 1 SLOE pulse sequence diagram.

Methods: In SLOE method, as illustrated in **Fig. 1**, an external oscillatory magnetic field was applied as the excitation pulse after a ΔB_0-B_1 insensitive spin-lock module [3], in place of the standard 90 degree excitation pulse in SIRS method. Hence the transverse magnitude $\boldsymbol{M}_{xy}$ excited by oscillatory fields was used to detect the neuronal currents instead of the reduction of $\boldsymbol{M}_z$. Since the spin-lock time (TSL) has large impacts on the detection sensitivity, a numerical simulation was applied to the time-dependent Bloch equation in the doubly rotating frame to determine the dependence of detection sensitivity on TSLs for both SLOE and SIRS methods.

Phantom and *in-vivo* experiments: A phantom study was performed to verify the simulation results on optimal TSL and compare the detection sensitivity of SIRS and SLOE. The phantom is composed of a single coil copper wiring wound around a plastic tube filled with $NiCl_2$ solution. A function generator was connected to the coil to generate oscillatory field in the direction of static field. The current was triggered to be on only during the spin-lock period [1]. For the rat study, the same scenario was employed with a copper coil wound around a hollow tube that covered on the rat's head. The MRI scans were performed on a 3T GE Discovery 750 MR scanner. A block-designed experiment was used with current on and off. Identical single slice acquisition parameters were used for both SIRS and SLOE in phantom: TR/TE = 1000 ms/24 ms, resolution = 0.96×0.96 mm^2, slice thickness = 6 mm. A smaller FOV was used in rats with resolution of 0.63×0.63 mm^2. The spin-lock field B_{SL} was fixed at 2.349 µT, corresponding to a resonant frequency at 100 Hz. The optimal TSL for both SIRS and SLOE were 160 ms and 100 ms, respectively. A comparison of detection sensitivity of SIRS and SLOE was made at different current levels with the frequency of oscillatory currents fixed at 100 Hz. A two-sample *t*-test was used to compare the signal differences during the on-blocks to that during the off-blocks voxel by voxel.

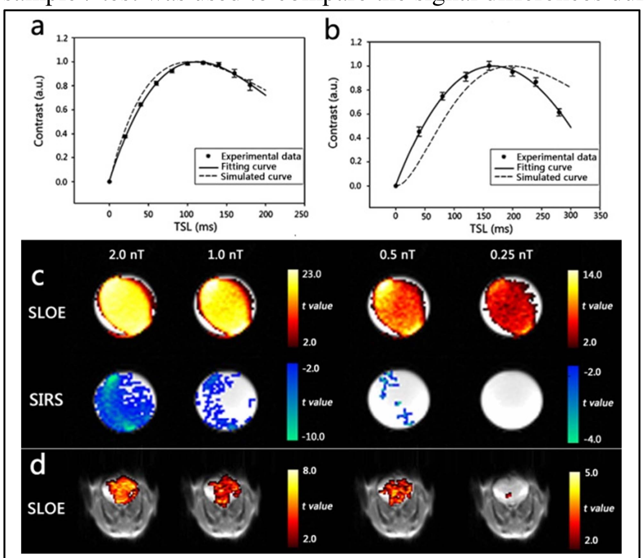

Figure 2 Detection sensitivity of (**a**) SLOE and (**b**) SIRS, as defined by the average ratio of on/off blocks. A least square fit was performed with measurements and error bars indicate the standard deviation across voxels in a ROI. Sensitivity maps of (**c**) SLOE and SIRS in phantom and (**d**) SLOE in rats. T-maps (cluster-level FWE corrected, p<0.05) are overlaid on a normal EPI image of the same slice.

Results: As shown in **Fig. 2a**, the experimental phantom results agreed well with the theoretical expectation in SLOE method. The reason for a shift of TSL observed in SIRS may be that the deteriorated SNR with long TSL affected the measurement (**Fig. 2b**). **Fig. 2c** shows the detection sensitivity of both SLOE and SIRS in varying field strengths from 2 nT to 0.25 nT calculated at the center of the field with their optimal TSLs. It is seen that, for phantom at higher field strength, both SIRS and SLOE performed well; however with a sub-nT (<1 nT) field strength, the SIRS method showed very little detection while SLOE still picked up a large portion of activation. Further, imaging results for *in-vivo* situation with applied oscillatory currents by SLOE sequence as shown in **Fig. 2d**, most of the voxels were still able to be significantly detected even the field strength was as small as 0.5 nT in the condition of the existence of physiological noise.

Discussion & Conclusions: Our proposed SLOE method showed extremely high detection sensitivity that enables 3T MR scanners for the first time to direct detect applied sub-nT oscillatory magnetic fields both in phantom and rats. The milestone achieved in this work paves the way towards direct mapping neuronal currents by MRI in the study of human brain function.

Reference: [1] T. Witzel, et al. NeuroImage. 2008; [2] X. Jiang, et al. MRM. 2014 (accepted); [3] W. Witschey II, et al. JMRI. 2007