Can Activation – Induced Neuronal Currents be Directly Detected using MRI?

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Introduction

Functional MRI techniques are essentially based on detection of hemodynamic changes accompanying neuronal firing changes, resulting in limitations in temporal resolution, spatial resolution, and interpretability. This abstract is an exploration of the feasibility of direct detection of neuronal current induced NMR phase and/or magnitude changes.

Methods

Our analysis was based on the hypothesis that a neuron, or neuronal bundle, exists in an infinite homogeneous conducting medium, and can be represented by an infinitely long cylindrical conductor, carrying uniform current. Neuronal activation was modeled by a current dipole described by Maxwell's quasi-static equations[1]. The "neuron(s)" diameter varied from 20μm to 1mm corresponding to the sizes ranging from that of a single axon to that of a patch of functionally similar cortex. The magnetic induction current range of 2nA to 1mA was estimated. Simulations were performed to evaluate the effects of the local neuronal magnetic fields on the MRI signal. Current induced magnetic field effects were assessed by varying the echo time, resolution, as well as neuronal orientation with respect to Bo.

The simulation results were compared with results from a "current phantom": a copper sulfate phantom with an electrically insulated thin copper wire (60mm in diameter)[2]. The study was performed on a 3T GE (General Electric, Milwaukee, WI) scanner with a temporal stability that allows for the detection of 2nT, or 0.5^0. Single shot EPI was used to obtain 256 images at TE: 30ms, and TR: 1s (FOV: 16cm, 4mm slice thickness, flip angle: 90, 64x64 resolution matrix). Current pulses were administered at 10s on, 5s off, varying the current intensity from 5μA to 100μA.

Results and Discussion

Based on the dipole neuron model formulated we found that active neurons can produce magnetic fields on the order of 0.1fT to 80nT depending on their diameter, orientation, and current capacity. Figure 1A illustrates the field and phase effects of an "active" 300μm neuronal bundle in a 2mm^3 homogeneous volume, at angles with respect to Bo [Bn: induced "neuronal" field; φ: phase shift; dφ: phase dispersion]. Figure 1B shows the phase distributions corresponding to the parallel orientation of the 300μm neuronal bundle (see arrow). Considering tissue in-homogeneity in a given imaging voxel, simulations yield the following: Assuming a linear neuronal structure parallel to Bo and imaging resolution of 1.5-3mm^3, we obtain field and phase changes averaging at 50nT, 24^0, with a phase dispersion of 100^0/mm^3. Given a "realistic" situation with random orientations, dendrite extensions, and cortical folding, the effects reduce to:

Voxel size →	3mm^3	2mm^3	1.5mm^3
Active region →	1.5mm^3	1mm^3	0.75mm^3
Total current →	50μA	33μA	25μA
Bneuronal (nT)	0.61	0.77	1.00
φ (^{0})	0.28	0.36	0.46
φ dispersion (^{0}/mm^3)	9.29	9.38	9.53

We observe that the estimated neuronal fields and phase shift are on the order of system detection levels. Detection of neuronal currents may critically depend on yet unclear aspects of dynamics and geometry configurations within imaging voxels. Regarding geometry, if the fiber bundles are of distributed orientations within a voxel, a minimal phase shift would occur. Instead, a subtle increase in phase dispersion (i.e. NMR magnitude decrease or decrease in T2*) would be detected. If neuronal orientation is homogeneous, then phase shifts may be more detectable. The spatial scale of the current distribution also determines the net phase shift and magnitude change. More extensive modeling is required to clarify the significance of variables in determining the optimal imaging strategy and delectability limits.

Preliminary results obtained from the phantom experiments yielded detectable magnetic field shifts for the range of current values used (5μA - 100μA).

Conclusion

The simulations and phantom experiments demonstrated the feasibility of using MRI to directly detect local magnetic field perturbations that can result from neuronal activation.

References

1. Plosney R. Biomagnetic Phenomena, McGraw-Hill, 1969.
2. Bodurka J., et al, J. Magn. Res. (1999), 137:265.

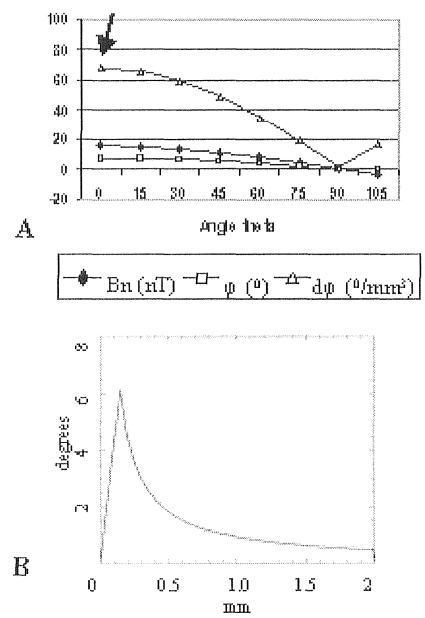

Figure 1. A) Induced field Bneuronal, phase shift φ, and phase dispersion dφ, of a 300 μm bundle,carrying 10 μA, at angles θ with respect to Bo. Resolution is set at 2mm^3; TE set at 30ms. **B)** Phase distribution created by a 300μm "neuronal" bundle carrying 10μA, parallel to Bo (arrow in figure 1A)