Neuronal current MRI: the effect of neuronal oscillations

Jiaxin Du[1], Viktor Vegh[1], and David C Reutens[1]
[1]*Centre for Advanced Imaging, The University of Queensland, Brisbane, QLD, Australia*

Introduction

Neuronal activity produces transient ionic currents that may be detectable using magnetic resonance imaging (MRI) technology. Theoretically, this effect, termed neuronal current MRI (nc-MRI), has the potential to map neuronal activity with higher spatial and temporal resolution than existing neuroimaging methods (1). Successful implementation of nc-MRI would benefit the study of brain function and may also have important clinical applications, for example in the non-invasive mapping of epileptic foci (2). However, nc-MRI is yet to be convincingly demonstrated and its feasibility is still debated (1). Through the use of computer simulations the feasibility of nc-MRI was studied.

Methods and materials

We used the laminar cortex model (LCM) to simulate neuronal activity of a grid of cortical columns (3). The LCM treats the same type of neurons within a column as a group, which acts as a single entity in a network of neurons. The neuron groups have similar features to single neurons, but their dynamics and connections are averaged using the mean-field approximation. A synaptic connection map is used to control neuron group connections (4). Cortical laminar architecture is incorporated in the LCM, enabling simulation of neuronal activity in three-dimensions. The LCM was developed to simulate the neuronal activity of the visual cortex and validated under different conditions of visual stimulation. We decomposed neuronal activities into action potentials (AP) and post-synaptic potentials (PSP). The geometries of the axons and dendrites that carry the APs and PSPs were generated dynamically. The magnetic fields of APs and PSPs were calculated separately and summed together to generate total neuronal magnetic fields (NMF), and their effect on MRI signals was calculated.

Results

To assess the influence of neuronal oscillation state on nc-MRI signals, two different oscillation states were generated using the LCM. Spontaneous activity corresponds to the activity in the primary visual cortex under natural visual stimulation and stimulated activity corresponds to activity induced by intermittent photic stimulation at a fixed frequency of 25 Hz. We also calculated the neuronal current induced MRI signal magnitude and phase changes in three voxels: voxel A, B and C (see Fig 1). Our main findings are 1) stimulated activity produced NMFs about four times larger than spontaneous activity (see Fig 2); 2) neuronal current induced MRI signal magnitude change is below 1 ppb for spontaneous activity and about 1 ppm for stimulated activity (see Fig 3), which is below currently detectable level; 3) the signal phase change is relatively larger, up to 15 μrad for spontaneous activity and 820 μrad for stimulated activity; 4) the signal phase changes are bigger at the boundary (voxel B) than inside (voxel A) and outside (voxel C) of the simulated neuronal activation region; 5) the signal phase change does not accumulate over time, instead it oscillates with neuronal activity.

Discussions

The signal differences between the spontaneous and stimulated activity and across the voxels predicted by our study may be explained by the temporal and spatial cancellation of NMFs. Temporal cancellation occurs because PSPs comprise changes with opposing phases reflecting membrane depolarization and repolarization which produce sequential changes in magnetic fields of opposite sign with opposing effects on signal phase resulting in cancellation over time. Spatial cancellation means a membrane potential change produces opposite magnetic fields on different sides of the axon/dendrite. If they are both included in a voxel, they may also cancel each other out, and contribute little to the mean NMF.

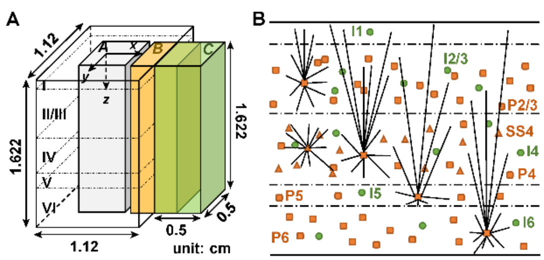

Fig 1 Structure of the model. The figure shows (A) the geometry of LCM simulated cortical region (transparent box) and three equal-size voxels (filled boxes), and (B) a sketch of cortical neurons and examples of dendrite tree structures.

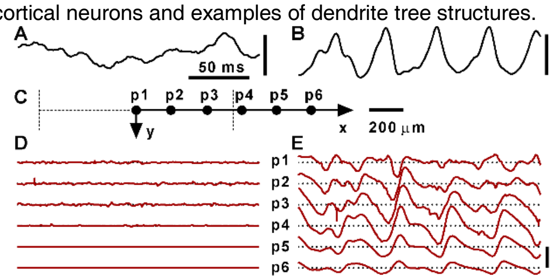

Fig 2 NMF time variations. Shown are the average neuronal firing rates of (B) spontaneous activity (scale bar: 0.001 spikes/s) and (B) stimulated activity (scale bar: 20 spikes/s), and the locations of six field points in the middle layer of the cortex (C) and the y-components of their NMFs during (D) spontaneous activity and (E) stimulated activity (scale bar: 500 pT).

A key prediction of our simulations is that synchronized neuronal activity produces periodicity in the signal phase (see Fig. 3). In view of this, the echo times (TE) for MRI acquisitions should be matched with the frequency of neuronal activity to maximize the chance of observing an effect. Our simulation study suggests that the optimal echo time is (n + 0.5) times the period of the major oscillation in neuronal activity(n is a non-negative integer), and MRI scans also need to be synchronized with neuronal oscillation to maximize the chance of detecting signal phase changes due to neuronal currents.

Conclusion

Our results suggest that the MRI signal phase changes produced by synchronized neuronal activity may be detectable with current MRI equipment whereas signal magnitude changes are below currently detectable levels. Signal acquisition timing and duration have to be appropriately chosen to maximise the effect of NMFs on the MRI signal.

References

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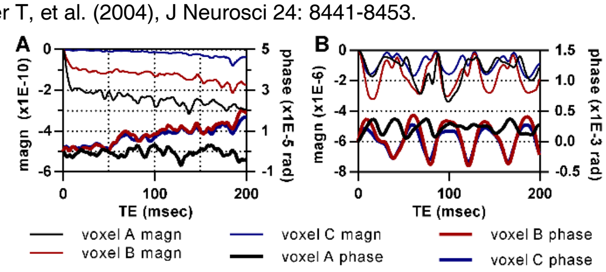

Fig 3 MR signal magnitude and phase changes induced by spontaneous activity (A) and stimulated activity (B). The signals were produced by y-components of NMFs.