Simulation Study of the Dendritic Effect on Direct MRI Detection of Neural Electric Event

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Abstract—Currently hemodynamic-based functional MRI technique is of limitation in temporal resolution. As neural activities in the brain accompany with current induced neuronal magnetic fields (NMF), it is possible to utilize MRI to detect NMF directly thus to improve the temporal resolution. In this work, the contribution of dendrite branch to NMF is investigated by numeric simulation. The results indicate that the existence of dendrite branch may enhance the detectability of NMF by MRI directly.

Index Terms—Dendrite branch, magnetic resonance imaging (MRI), neural activity, neuronal magnetic field.

1. Introduction

Neural activities in the brain involve electrochemical currents, which may produce transient and weak magnetic fields. These neuronal magnetic fields (NMF) are detectable even at the scalp, which is 2 cm to 4 cm away from the sources, using magnetoencephalography (MEG) [1]. Obviously, at the sources, the NMF will be much stronger, and the component of the NMF, \( B_{\text{sca}} \), parallel to the \( B_s \) (of the scanner) will cause the sample’s spins rotating with different precession frequency. These spins experience additional phase and a loss of phase coherence, which in turn result in a decrease in the MRI signal. Though the NMF will cause change in the MR signal, whether the change strength can be detectable is still a matter of debate in theory and practice.

Previous works have shown that MRI can directly detect transient and weak magnetic field on phantoms [2], [3]. Meanwhile, successful mapping of neuronal activity in the human brain by direct MRI detection was reported by Kamei et al. and Xiong et al. [4], [5]. Further evidence indicating the feasibility of MRI detection of NMF was from the researches of Vologov et al. and Liston et al. [6], [7]. Nevertheless, contradictory to the above findings, Parkes et al. reported that no MRI signal related NMF was detected in their experiments [8].

In this paper, as the main dendrites in the brain have amount of branches, the dendrite branch is taken into account to investigate its contribution to the NMF by numeric simulations. The feasibility of direct detection of NMF by MRI is analyzed based on the assumption that the minimal value of the NMF which can be directly detected in a MRI experiment is 1 nT [9].

2. Theoretical Model for NMF

2.1 Source for NMF

Electromagnetic field is generated from the neuronal activities in the brain. Generally, a neuronal cell typically consists of a soma, a single axon and multiple dendrites. The electromagnetic field is originated from the action potentials (APs) propagating along the axons, and the postsynaptic potentials are caused by the electric ion transmission in the dendritic tree of the neuronal cell. Since the postsynaptic potentials sum up in a graded manner, yielding a temporally modulated and longer-lasting (50 ms to 200 ms) dipolar magnetic field, the signal source of NMF is probably the postsynaptic potentials and the effects of the axons can be ignored [10]. Consequently, when calculating the NMF, we only consider the dendrites and use the dendrites model as the whole single neuron.

2.2 Biot-Savart Law

Neuronal activity in the brain involves electric current, which produces magnetic field. The magnetic vector field, \( B \), caused by a neuronal current density \( J \) located at \( r' \), is [11]:

\[
B(r,t) = \frac{\mu_0}{4\pi} \int J(r',t) \times (r-r') \left/ (r-r') \right. dr' + \frac{1}{4\pi\sigma} \int \frac{\partial J(r',t)}{\partial t} \times (r-r') \left/ c|r-r'|^2 \right. dr'
\] (1)
where \( \mu_0 \) is the permeability of the brain tissue, \( \sigma \) is electrical conductivity, \( c \) is the speed of the electromagnetic wave. In brain electromagnetism, the quasi-static approximation of Maxwell’s equations is generally valid \(^{[11]} \). Then the second term in (1) can be omitted. Meanwhile, since the extracellular current is two orders smaller than the intracellular current, it has little effect on the MRI signal and can be safely ignored \(^{[12]} \). Therefore, the magnetic field induced by the intracellular current \( I_i \) can be calculated according to Biot-Savart law:

\[
B_{mn}(r,t) = \frac{\mu_0}{4\pi} \int \frac{I(r,t) \times (r-r')}{|r-r'|^3} d^3r . 
\]

(2)

3. Calculation of NMF

3.1 Single Neuron Model

To build a realistic model of neuron, each dendrite or each dendrite branch is modeled as a finite current-dipole, as shown in Fig. 1 (a). Theoretically, both intracellular current \( I_i \) and extracellular current \( I_e \) will contribute to the NMF. However, as mentioned above, the extracellular current is far smaller than the intracellular current and its effect on the MRI signal can be safely ignored. For convenience, we define the current, along the \( z \) axis, flows along the dendrite, and the \( B_0 \) field is along the \( y \) axis, as shown in Fig. 1 (b). For any observation point \( P \) outside a dendrite, magnetic field can be calculated according to (2).

3.2 Parameter Selections

Since the dendrites and their branches are different in size and pattern, the choice of the dendrite parameters is very important. In our model, the following parameters are adopted: radius of dendrite: 0.25 \( \mu \)m to 0.5 \( \mu \)m \(^{[13]} \), length of dendrite: 1 mm \(^{[14]} \), and intracellular current: 1 nA to 5 nA \(^{[15]} \).

Based on the Biot-Savart law, the greatest strength of the magnetic field (in the surface of dendrite) increases in direct proportion to the intracellular current and decreases in inverse proportion to the radius of dendrite, thus different combination of the intracellular current and radius will result in a different magnetic field strength, i.e., the larger the current radius ratio, the greater the magnetic field strength. Since the aim of this paper is to investigate the feasibility of the direct detection of NMF by MRI, the minimum current radius ratio (the intracellular current is 1 nA and the radius of dendrite is 0.5 \( \mu \)m) will be usually used for the main dendrite in order to find out the minimum measurable value by MRI. However, for comparison, the maximal current radius ratio is also adopted sometime (the intracellular current is 5 nA and the radius of dendrite is 0.25 \( \mu \)m).

3.3 NMF Distribution for Single Dendrite Model

Fig. 2 shows component of the induced magnetic field parallel to \( B_0 \), along the \( y \) axis, for a dendrite with minimum current radius ratio. The magnetic field is concentrated around the dendrite, and the magnitude of magnetic field has the maximum value on the surface of the dendrite, and then decays rapidly. The magnetic field on the right side of the dendrite is opposite to that on the left side.

Fig. 3 (a) and (b) show the magnetic field along the \( x \) axis for maximal current radius ratio and minimum current radius ratio respectively. The magnetic field peak value of the former is one order larger than that of the latter. Hence, the choice of the ratio will have great effect on our next study.
3.4 Effect of Dendrite Branch

Since the dendrite branch is widespread, its existence may necessarily influence the NMF and the effect of dendrite branch should depend on the branch’s orientation, i.e. the included angle between the main dendrite and its branches. Meanwhile, as what we concern most is the greatest strength of the NMF, we will only consider the point where the dendrite and its branch intersect.

To study the minimum measurable value, we considered the inphase configuration between the main dendrite and its branches. In this condition, the magnitude signal decreases with the cosine of the included angle, as shown in Fig. 4. Fig. 5 shows the magnetic field induced by the inphase configuration. For the minimum current radius ratio, the necessary included angle should be not more than 1.4 rad, corresponding to the critical value, so as to ensure that the magnetic field is up to 1 nT. When the included angle is zero, we can obtain the greatest magnetic field that is up to 4.4 nT.

The above calculation is based on the inphase configuration. Since the antiphase configuration between the main dendrite and its branch is realistic existence in the brain, we should take this situation into account. Distinguishing from the inphase configuration, the absolute value of the magnetic field raises with the included angle, as shown in Fig. 6. In this section, we use the max current radius ratio for the main dendrite and its branch. Fig. 7 shows the magnetic field induced by the antiphase configuration. Corresponding to the critical value, the included angle is 0.7 rad. When the included angle is greater than this value, the magnetic field will be detectable.

4. Conclusions

In this paper, we simulated the NMF using dendrite model as a finite current-dipole, and investigated the feasibility of the direct detection of NMF by MRI. We discussed the contribution of dendrite branch to NMF, and our results implicated that the existence of dendrite branch may greatly enhance the detectability of NMF by MRI directly. In the future, we will continue our work with models which are more approximate to the realistic neuron.

![Fig. 4](image-url) Fig. 4. The relationship between the included angle and the generated magnetic field for the inphase configuration.

![Fig. 5](image-url) Fig. 5. The magnetic field along the x axis for the inphase configuration: (a) the magnetic field along x axis using the minimum intercellular radius ratio for the main dendrite, (b) based on (a) and (c), the critical value of magnetic field generated by the dendrite branch. The dendrite branch uses the maximal intercellular radius ratio, and (c) the minimum measurable value of the NMF which can be directly detected by MRI.

![Fig. 6](image-url) Fig. 6. The relationship between the included angle and the generated magnetic field for the antiphase configuration.

![Fig. 7](image-url) Fig. 7. The magnetic field along the x axis for the antiphase configuration: (a) the magnetic field along x axis using the maximal intercellular radius ratio for the main dendrite, (b) based on (a) and (c), the critical value of magnetic field generated by the dendrite branch. The dendrite branch uses the maximal intercellular radius ratio, and (c) the minimum measurable value of the NMF which can be direct detection by MRI.

References

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