Lorentz Effect Imaging of Ionic Currents in Solution

T-K. Truong[1], A. Avram[1], and A. W. Song[1]

[1]Brain Imaging and Analysis Center, Duke University, Durham, NC, United States

Introduction

Existing fMRI techniques relying on hemodynamic modulations such as BOLD fMRI are widely used to investigate the function of the human nervous system, but are inherently limited in their ability to accurately localize neural activity in space and time. As such, there has been an increasing interest over the past few years in the development of novel MRI techniques that can directly image neural activity *in vivo*, thereby combining the high temporal resolution of modalities such as EEG and MEG with the noninvasiveness and high spatial resolution advantages inherent in MRI. Among these, Lorentz effect imaging was proposed to detect spatially incoherent yet temporally synchronized minute electrical activity in a strong magnetic field. Its ability to directly image electrical currents on the order of microamperes with a temporal resolution on the order of milliseconds was demonstrated in gel phantoms [1]. More recently, it has been successfully applied to directly image neuroelectric activity *in vivo* in the human median nerve during electrical stimulation of the wrist [2]. Such a real-time and noninvasive neuroimaging technique could potentially find broad applications in neurosciences. To better characterize its contrast mechanism and further improve its sensitivity for *in vivo* applications, we apply this technique to image ionic currents in solution, which are more relevant to neural conduction in biological systems and differ from the electronic currents in conductive wires used in previous phantom studies.

Methods

An ion with a charge q and a velocity **v** exposed to an electric field **E** and a magnetic field **B** experiences a Lorentz force $\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$. Thus, the ions contained in an ionic solution exposed to a uniform static magnetic field and a spatially varying (*e.g.*, dipolar) electric field experience a spatially incoherent displacement induced by the Lorentz force. Consequently, the water molecules surrounding these ions also experience such a spatially incoherent displacement. The application of a magnetic field gradient causes a dephasing of these spins proportional to its amplitude and duration, which in turn results in a signal loss within a voxel. Multiple cycles of oscillating gradients synchronized with the Lorentz force can be applied to amplify the loss of phase coherence, and thus significantly increase the sensitivity of the technique [1,2].

To demonstrate this effect in ionic solutions, a 10-cm diameter spherical phantom containing a 2.8 g/l $CuSO_4$ solution was constructed with two diametrically opposed copper wire electrodes. Axial gradient echo images containing both electrodes were acquired on a 4 T MRI scanner using TR 150 ms, TE 71 ms, flip angle 60^o, FOV 12 cm, matrix size 256×128, slice thickness 5 mm, and 15 cycles of oscillating gradients with an amplitude of 36 mT/m and a duration of 2 ms for each lobe applied along both the frequency and phase encoding directions. The resulting b-factor was only 3 s/mm^2, thus causing negligible signal attenuation due to diffusion weighting. The electrodes were connected via shielded cables to a square wave pulse generator triggered by the scanner such that the current was turned on only during the positive lobes of the oscillating gradients. The ionic current was varied from –2 mA to 2 mA.

Results and Discussion

The acquired images (**Fig. 1A**) clearly show signal loss along a curved trajectory between the two electrodes (mounted on the left and right sides of the phantom, as indicated by the susceptibility artifacts) that increases with the current amplitude. This graded effect can be better seen by subtracting a reference image acquired without current from each image (**Fig. 1B**) and demonstrates the contrast dependence on the amplitude of the ionic current. The trajectory is curved upwards or downwards for negative or positive currents, respectively, as predicted by the direction of the Lorentz force. Although signal loss due to the Lorentz effect is predominant, there are also significant flow effects along the trajectory of the ionic current, which can help enhance the contrast in the presence of oscillating gradients.

The contrast dependence on the externally applied oscillating gradients was also examined in a control experiment, wherein the gradients were turned off. As expected, no signal loss was observed. These two experiments confirm the basic contrast mechanism of Lorentz effect imaging in ionic solutions, thus opening avenues for further investigations to improve its sensitivity and extend it to biological systems.

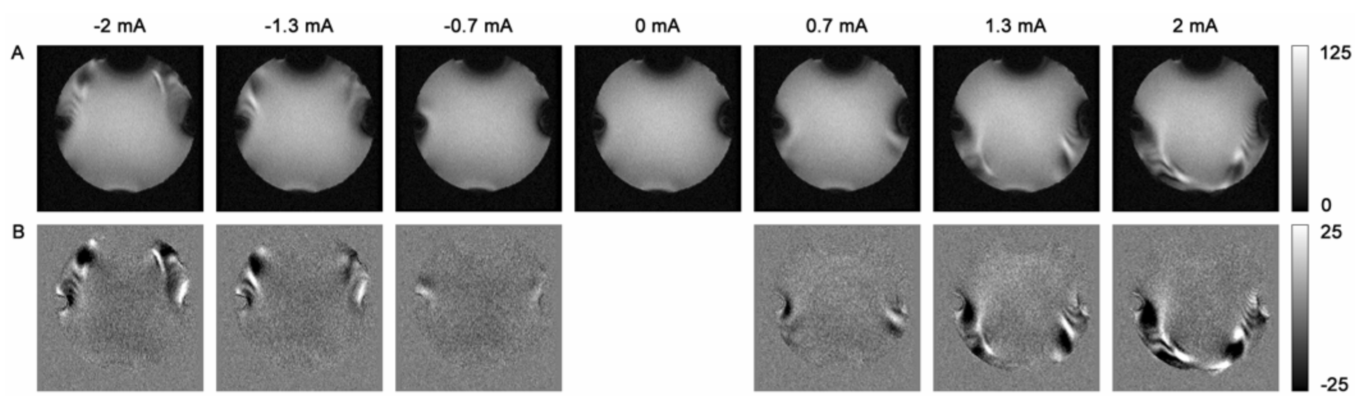

Fig. 1: (**A**) Axial images of the phantom acquired with different current amplitudes and polarities. (**B**) Difference images with the reference image acquired without current. The positive and negative electrodes are located on the left and right side of the phantom, respectively, and the static magnetic field points out of the image plane.

Conclusion

Our preliminary results have demonstrated the feasibility of Lorentz effect imaging in ionic solutions and provided a basic understanding of its contrast mechanism. The characteristic dual dependence on ionic current amplitude and oscillating gradients was observed. Further studies are currently underway to improve the sensitivity of this technique and optimize it for *in vivo* applications.

References: [1] Truong *et al*. JMR 2006;179:85–91. [2] Truong *et al*. PNAS 2006;103:12598–12601. This work was supported by NSF grant BES 0602529.