Magnetohydrodynamic effects in MRI studies of ionic-current phantoms: dependence on field strength and conductivity

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Introduction: Understanding the behavior of ionic volume currents in the presence of strong magnetic fields could facilitate efforts to use MRI to detect signals more tightly coupled to neuronal activity than the hemodynamic response. However, studies on this topic are controversial: two competing mechanisms have been proposed to explain the MRI results of Truong et al. [**1**] on volume currents—their Lorentz effect (LE) model and the magnetohydrodynamic (MHD) model proposed (but not experimentally tested) by Wijesinghe et al. [**2**]. In previous work [**3**], we tested (and confirmed) one central prediction of the MHD model: that the spatial pattern of MRI phase signals evolves slowly (on the order of a minute) for ionic currents in normal (0.9%) saline at 3T. Here, we test two further predictions of MHD: that the evolution of these phase patterns will be strongly influenced by (i) the main magnetic field strength B_0 and (ii) the conductivity σ of the fluid.

Background and Theory: Truong et al. [**1**] studied volume currents in a phantom at 4T and observed a large apparent displacement of the currents in a direction orthogonal to the main magnetic field $\mathbf{B}_0$, an effect they explain with a simple mechanism incorporating the Lorentz force law and a drag term (the LE model). However, Wijesinghe and Roth [**2**] point out that when realistic values of ion mobility are used in the LE model, the predicted displacement of the volume currents is negligible and they instead propose MHD flow as the explanation of the observed displacements.

Under certain conditions (e.g., constant electric and magnetic fields), the characteristic time τ over which MHD flow develops can be mathematically derived and shown to be $\tau = \rho/(\sigma B_0^2)$ [**4**], where ρ is the density of the solution. For 0.9% saline, ρ and σ are 1000 kg/m^3 and 1.5 S/m, respectively, resulting in $\tau = \rho/(\sigma B_0^2) \approx 80$s at B_0 = 3T. Note that if the conductivity σ is increased to 6 S/m (e.g., by using 3.6% saline), τ is reduced to ~20s, but if the main magnetic field B_0 is then changed to 1.5T, τ returns to a value of ~80s.

Methods: Two phantoms were constructed for this study, based on methods initially described in [**5**]. For Phantom 1, two glass capillary tubes (1.2 mm inner diameter, 1.6 mm outer diameter) were embedded inside a plastic bottle, with the tubes running parallel to $\mathbf{B}_0$, as shown in Fig. 1. The bottle and the capillary tubes were filled with a solution of 1 L normal saline (0.9%) and 1 mL of gadopentetate dimeglumine (Magnevist, Berlex Laboratories). Chloridized silver electrodes were inserted into the two capillary tubes, in the section of these tubes that extended outside the bottle. The two electrodes were connected to a twisted-pair cable leading to a signal generator and a 10 kΩ resistor, connected in series, in the scanner console room. This setup allowed us to pass ionic direct currents through the volume of the phantom, from the end of one capillary tube to the other, as shown schematically with the blue arrows in Fig. 1. Phantom 2 was built in an identical manner, but with 3.6% saline, resulting in four times the conductivity; a 2.5 kΩ series resistor was therefore used with this phantom. For each MRI scan, 6V was applied across the entire circuit (with ~0.6V measured across the series resistor) for 150 seconds, following a 150s baseline period, corresponding to a square-wave current of ~60 μA (Phantom 1) or ~240 μA (Phantom 2). Although the currents were different for the two phantoms, the potential difference across the capillary-tube ends, and therefore the electric field in the phantoms, was almost the same.

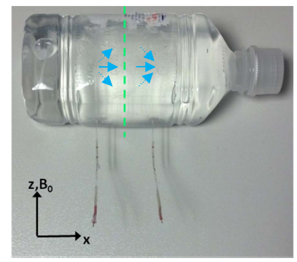

Fig. 1: Ionic current phantom. Positive currents flow into the left capillary tube, through the volume of the phantom (schematic blue arrows), and out of the right capillary tube.

The MRI scans were performed on either a Siemens 3T Trio or a 1.5T Avanto scanner equipped with a 12-channel receive array coil. Gradient-echo EPI scans were acquired with the following parameters: TR 750 ms, TE 32 ms, BW 2298 Hz/pixel, flip angle 20°, 64x64 matrix, FOV 220x220 mm, and 5 mm slice thickness. Each EPI run lasted 450 seconds, consisting of magnitude and phase images at 600 time points. For each voxel, the phase time course was quadratically detrended and the average baseline value was subtracted out. The resulting time course was divided into 15-second bins and the average value within each bin was computed. This process was repeated for each voxel in the "mid-sagittal" slice indicated in Fig. 1 (green dashed line) and the resulting image was smoothed with a 3x3 boxcar filter in order to produce the phase-change images shown in Fig. 2.

Results: Phase-change images for low-conductivity Phantom 1 at 3T (Fig. 2, top row) show a pattern that is only fully developed around 60-80s after current onset. A more rapid evolution is seen for high-conductivity Phantom 2 at 3T (Fig. 2, middle row), with the final phase pattern appearing to be almost fully established by the time bin centered at 37.5s. When Phantom 2 was scanned at 1.5T (with all other conditions kept unchanged from the experiment at 3T), a slower development of the phase pattern (taking ~70s to establish) was once again observed (Fig. 3, bottom row). The data and results are noisier at 1.5T than at 3T, as expected.

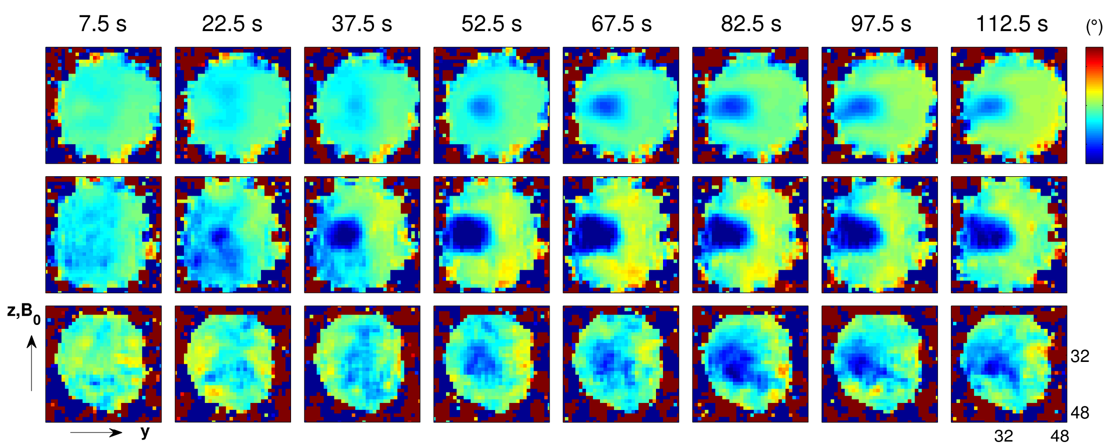

Fig. 2: Phase-change (-3° to 3°) images for Phantom 1 (σ = 1.5 S/m) at 3T (top row), Phantom 2 (σ = 6 S/m) at 3T (middle row) and Phantom 2 at 1.5 T (bottom row). The time after current onset (specifically, the time-bin center) corresponding to each column of images is shown above the column.

Discussion: The results shown in Fig. 2 all exhibit spatial patterns of phase that take tens of seconds to develop. In contrast, the LE model [**1**] predicts signals that will develop almost instantaneously (on the order of microseconds). Although not all of the conditions assumed in the derivation of the MHD characteristic time τ are met in our experimental setup (e.g., the electric field in the phantom is not uniform in space when the current is on), we nevertheless observe development times that are in approximate agreement with τ as we vary the magnetic field strength B_0 and the conductivity σ. Our results therefore provide further experimental support for the MHD hypothesis proposed by Wijesinghe and Roth [**2**], and we conclude that understanding and accounting for MHD flow effects could be an important aspect of MRI studies in which significant ionic volume currents are likely to be encountered.

References: [**1**] Truong et al. (2008) *J Magn Reson* 191:93-99. [**2**] Wijesinghe and Roth (2010) *J Magn Reson* 204:225-27. [**3**] Balasubramanian et al. (2013). *ISMRM* 21:3361. [**4**] Jackson (1975) *Classical Electrodynamics (2nd ed.)* [**5**] Balasubramanian et al. (2012) *ISMRM* 20:2887.