Gradient-echo imaging of ionic currents in solution

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Introduction: Understanding the behavior of ionic volume currents in the presence of strong magnetic fields could assist efforts to use MRI to detect epileptiform discharges [1], especially when these discharges occur near cerebrospinal fluid spaces such as the lateral ventricles. However, studies on this topic are controversial: two competing mechanisms have been proposed to explain the MRI results of Truong et al. [2] on volume currents—the Lorentz effect (LE) model [2] and the magnetohydrodynamic (MHD) model [3]. Here, we address this controversy by directly testing the MHD hypothesis using an ionic current phantom through which volume currents of varying duration were applied. Our results provide experimental support for the MHD model proposed by Wijesinghe and Roth [3].

Background and Theory: Truong et al. [2] 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 [3] point out that when realistic values of ion mobility (taken from the literature) are used in the LE model, the predicted displacement of the volume currents is negligible. Instead, they propose MHD flow as the explanation of the displacements observed by Truong et al. Since MHD flow takes a characteristic time $\tau = \rho/(\sigma B_0^2)$ to develop, where ρ and σ are the density and conductivity of the solution, respectively, a central prediction of the MHD hypothesis is that the spatial pattern of the volume currents will depend on the duration t_d of the applied current relative to the characteristic time τ—a prediction we test experimentally, as described below.

Methods: The construction of the ionic-current phantom was described previously [4]. Briefly, 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 saline (0.9%) and 1 mL of gadopentetate dimeglumine (Magnevist, Berlex Laboratories). For 0.9% saline, ρ and σ are 1000 kg/m^3 and 1.5 S/m, respectively, resulting in $\tau = \rho/(\sigma B_0^2) \approx 75$ s at $B_0 = 3$T. 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 with 60 μA amplitude and varying duration (square waves with an "on" time t_d ranging from 15 to 150 seconds) 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. All experiments were performed on a Siemens 3T Trio 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 15 slices with 5 mm slice thickness. Each EPI run lasted 750 seconds, consisting of magnitude and phase images at 1000 time points. Quadratic trends were removed from the EPI time series for each voxel in order to discard scanner drift effects and the (Pearson) correlation coefficient between the time course of the applied current and the time series for each voxel was computed, resulting in magnitude- and phase-correlation maps for each EPI run, as in Bodurka et al. [5].

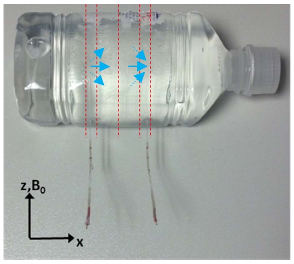

Fig. 1: Ionic current phantom. Positive currents flow into the left capillary tube, through the volume of the phantom (schematic blue arrows), and out of the right capillary tube.

Results and Discussion: The phase-correlation maps shown in Fig. 2 demonstrate a clear dependence on the duration t_d of the applied currents. Furthermore, the correlation maps for the shortest duration ($t_d = 15$ s $\approx \tau/5$) correspond to what would be expected if the volume currents were largely unaffected by $\mathbf{B}_0$, with high current density near the capillary tube ends (Slices 1, 2, 4 and 5) and low current density at the center (Slice 3). The magnitude-correlation maps (not shown) exhibit similar properties, albeit with weaker correlation strengths. These results provide experimental support for the MHD hypothesis proposed by Wijesinghe and Roth [3]. We therefore conclude that understanding and accounting for MHD flow effects could be important for future MRI studies in which significant ionic volume currents are to be expected.

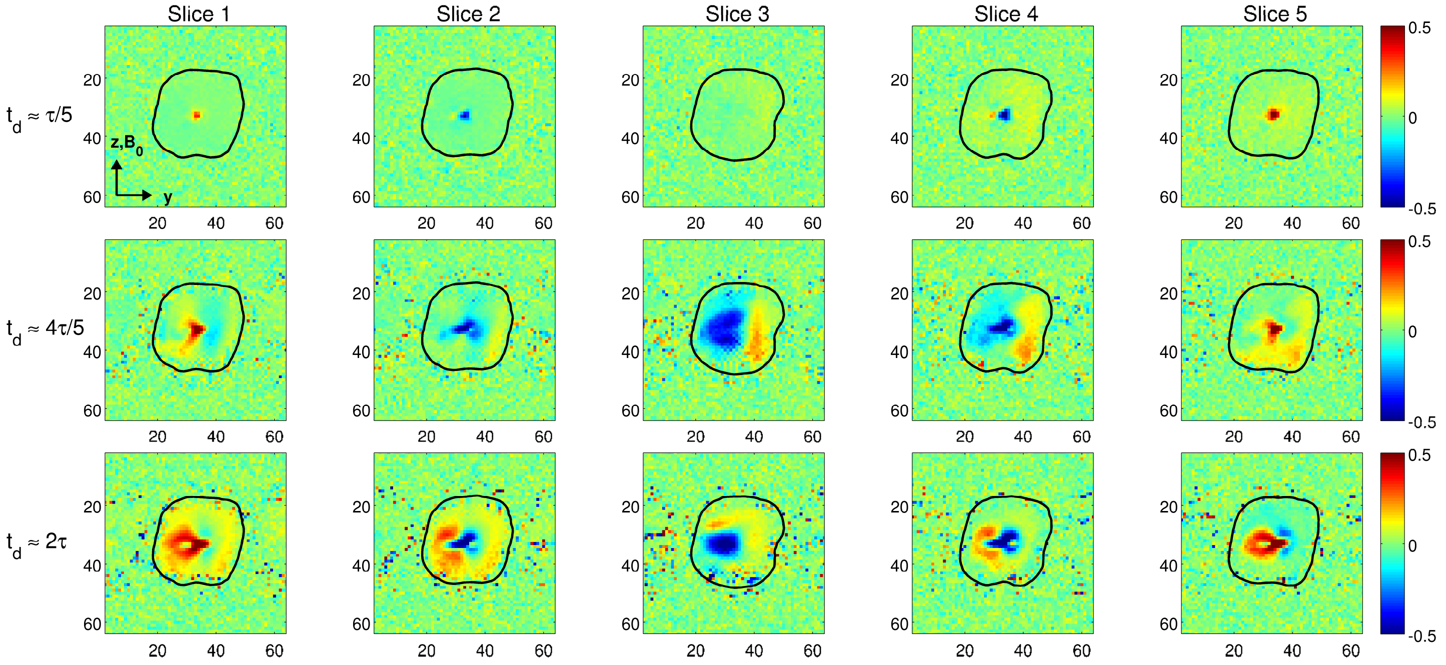

Fig. 2: Phase-correlation maps for currents with varying duration. Top row: $t_d = 15$ s ($\approx \tau/5$). Middle row: $t_d = 60$ s ($\approx 4\tau/5$). Bottom row $t_d = 150$ s ($\approx 2\tau$). Due to space limitations, only five of the fifteen acquired slices are shown, indicated by the red dashed lines in Fig. 1. The black curves indicate the boundary of the phantom.

References: [1] Sundaram et al. (2010) *Magn Reson Med* 64:1728-38. [2] Truong et al. (2008) *J Magn Reson* 191:93-99. [3] Wijesinghe and Roth (2010) *J Magn Reson* 204:225-27. [4] Balasubramanian et al. (2012) *ISMRM* 20:2887. [5] Bodurka et al. (1999) *J Magn Reson* 137:265-71.