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

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 the main magnetic field \( B_0 \), 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 mm thickness bottle was used instead of the one used for Phantom 1. Positive currents flow into the left capillary tube, through the series resistor (with \(-0.6\) V measured across the series resistor) for 150 seconds, following a 150s baseline period, corresponding to development of the phase signals that will develop almost instantaneously (on the order of microseconds). Although not all of the conditions assumed in the derivation of the MHD model were 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 \( \tau \) as we vary the magnetic field strength \( B_0 \) and the conductivity \( \sigma \). 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.