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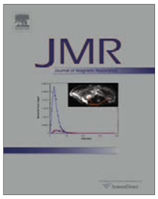

Lorentz effect imaging of ionic currents in solution using correct values for ion mobility

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ABSTRACT

Truong and his colleagues have recently published a paper introducing a new method called Lorentz effect imaging (LEI) to detect ionic currents in a solution. Their main goal was to prove that the Lorentz force acting on ions in the presence of a static magnetic field could be used as a contrast mechanism to measure neural currents with magnetic resonance imaging. However, they failed to use the correct values for the ion mobilities. In this investigation, we have used correct ion mobility values and show that LEI cannot be used as a contrast mechanism to directly image neural currents.

1. Introduction

Truong, Avram and Song recently published a report on "Lorentz effect imaging of ionic currents in solution" [1]. Their goals were to determine the effect of magnetic forces on moving ions and to evaluate the potential use of Lorentz forces as a contrast mechanism for imaging neural currents with magnetic resonance imaging. Truong et al. considered an ion with a charge q and mass m, moving with velocity $\mathbf{v}$ in an ionic solution exposed to an electric field $\mathbf{E}$ and a magnetic field $\mathbf{B}$. The equation of motion of the ion contains three forces: an electric force $q\mathbf{E}$, a magnetic force $q\mathbf{v} \times \mathbf{B}$ (together called the Lorentz force), and a drag force $-b\mathbf{v}$

$$q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - b\mathbf{v} = m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}. \qquad (1)$$

In their simulations, they modeled the motion of copper and sulfate ions (these were the ions used in their experiments). Their results showed that the ions "follow trajectories that are curved downwards as predicted by the direction of the Lorentz force". Truong et al. concluded that "ionic currents with durations and current densities on the same order of magnitude as those induced by neuroelectric activity in nerve fibers and in the brain can be detected" [1].

Consider Eq. (1) and ignore for the moment the magnetic field. Assuming that the ion has reached a terminal velocity (its acceleration is zero), we find that $\mathbf{v} = \mathbf{E}(q/b)$. Thus, the factor q/b plays the role of the ion mobility, u (the speed of the ion divided by the electric field strength). For the copper ion, Truong et al. let $q = 3.204 \times 10^{-19}$ C and $b = 2.5 \times 10^{-18}$ kg/s, implying $u = 0.128$ C s/kg, or 0.128 (m/s)/(V/m). The measured mobilities of several ions are given in Table 1, and are on the order of 7×10^{-8} (m/s)/(V/m).

To estimate the importance of the magnetic part of the Lorentz forces on the movement of ions, we can form a dimensionless number R by taking the ratio of the magnetic force (qvB) to the electric force (qE), or R = vB/E. If R is on the order of one, magnetic forces and electric forces are approximately equal. If R is much less than one, magnetic forces are small compared to electric forces. We can estimate v using the mobility, v = uE, so that the electric field cancels in the ratio and $R = u$B. If we use Truong et al.'s values for the mobility, 0.128, and the magnetic field, 4 T, then R is 0.51. If we instead use the mobility of a sodium ion, 5.2×10^{-8}, then R is 0.21×10^{-6}. Thus, Truong et al.'s simulations appear to have overestimated the influence of the magnetic part of the Lorentz force by more than a factor of one million, compared to what one would expect during nerve conduction. Lorentz forces will be more difficult to detect using magnetic resonance imaging than Truong et al. suggest.

2. Methods

We solved the differential equation given by Eq. (1) numerically using the Euler method [4] on the Ball State University Beowulf computer cluster, which is a 32-node computer with 64 2.8 GHz Xeon processors. We used 10 ps time increments when evaluating derivatives of the variables in the differential equation. The computing time for the trajectories shown in the figures ranged from

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Table 1
The magnitude of measured mobilities of ions in water[a].

Ion	Mobility (m/s)/(V/m)	Source
Sodium	5.2×10^{-8}	[2]
Potassium	7.6×10^{-8}	[2]
Chlorine	7.9×10^{-8}	[2]
Copper	5.4×10^{-8}	[3]
Sulfate	8.0×10^{-8}	[3]

[a] The mobility depends on the temperature (all data for 25 °C) and the ion concentration.

0.5 to 4.5 h defending upon the initial condition used for the trajectory.

Following their assumptions, we also assumed that the copper and sulfate ions were initially at rest in the vicinity of the positive and negative electrodes, respectively. We used the same parameters that they used to create the trajectories given in their Fig. 2: $q(\mathrm{Cu}^{2+}) = 3.204 \times 10^{-19}$ C, $q(\mathrm{SO}_4^{2-}) = -3.204 \times 10^{-19}$ C, $m(\mathrm{Cu}^{2+}) = 1.055 \times 10^{-25}$ kg, $m(\mathrm{SO}_4^{2-}) = 1.595 \times 10^{-25}$ kg, the distance between two electrodes, $d = 10$ cm, the absolute voltage of the electrodes, $U = 5$ V, magnetic field, B = 4 T and $b = 2.5 \times 10^{-18}$ kg/s. We also assumed that the static magnetic field is in the z-direction. Fig. 1 shows the trajectories of the copper and sulfate ions we obtained during our calculation. This figure is very similar to Fig. 2 of their paper. If we had the access to initial positions of the ions that they used in their simulations, we could have been able to recreate their figure exactly. However, when we used the correct values for the mobility of copper and sulfate ions listed in Table 1 and the other parameters listed above with the same initial conditions used to create Fig. 1, we obtained trajectories of the copper and sulfate ions as shown in Fig. 2. The copper and sulfate ions take a completely different path than the one claimed by Truong et al. In fact, trajectories just follow the electric fields lines almost exactly. This calculation therefore shows that the main force acting on the ions is the electric force created by the electrodes in their experimental setup. The effect of the magnetic part of the Lorentz force on the ions is negligible.

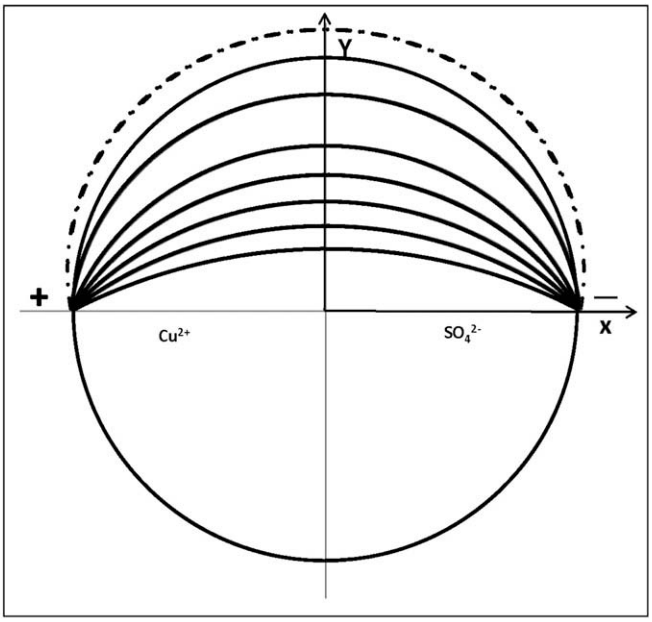

Fig. 2. Simulated trajectories of Cu^{2+} and SO_4^{2-} ions in a sphere exposed to a uniform static magnetic field and a dipolar electric field induced by two electrodes located on each side of sphere with correct values for ion mobility. The stream lines are restricted to half the plane because we have used the same initial conditions that were used in simulating trajectories in Fig. 1. Had we chosen a symmetrical distribution of initial conditions, the streamlines would be symmetrically placed in the upper and lower parts of the plot.

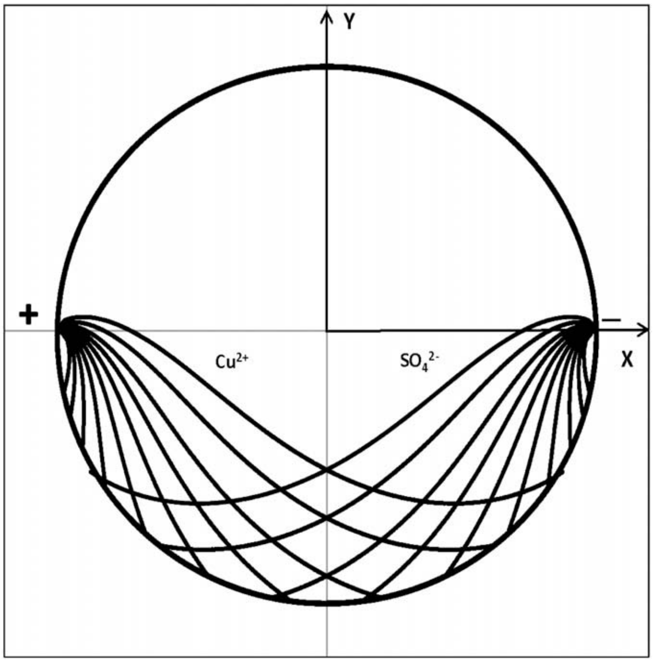

Fig. 1. Simulated trajectories of Cu^{2+} and SO_4^{2-} ions in a sphere exposed to a uniform static magnetic field and a dipolar electric field induced by two electrodes located on each side of sphere as proposed by Truong et al. We have used the same parameters that they used to create Fig. 2 of their paper.

This investigation proves that the magnetic part of the Lorentz force cannot be used as a contrast mechanism for imaging ion currents during the magnetic resonance technique.

Another mechanism that could affect the MR signal is magnetohydrodynamically induced flow [5]. A conducting fluid in crossed magnetic and electric fields will tend to flow with a speed on the order of E/B = (50 V/m)/(4 T)=12 m/s. However, this flow develops over a time equal to $\rho/\sigma B^2$, where ρ is the density of the fluid and σ is the conductivity. Truong et al. measured $\sigma = 140$ S/m, so the time is $(1000\ \mathrm{kg/m^3})/(140\ \mathrm{S/m}\ 16\ \mathrm{T^2}) = 0.4$ s. The current pulses are only on for about 30 ms, so the induced speeds were probably closer to 1 m/s. Nevertheless, such a flow should result in a significant artifact in the MR signal, and may be what Truong et al. observed. Scott et al. [6] observed magnetohydrodynamic effects during their MR measurement of current. Such an effect should be smaller in tissue because of the factor of 100 smaller conductivity and because of the restricted flow of water in a porous tissue. Both the effect examined by Truong et al. and the magnetohydrodynamic effect arise from the Lorentz force, but they otherwise are very different mechanisms. Magnetohydrodynamic flow depends on the density of the fluid, the conductivity (and therefore the concentration of the ions) and is caused by a bulk flow of the fluid, whereas the Lorentz force analyzed by Truong et al. is independent of these factors.

We have shown that the model presented in Truong et al.'s paper cannot explain their experimental data. We do not question the data itself, but just their interpretation. Our calculations show that their mechanism of magnetic forces acting on individual ions causing an effect on their motion is not tenable. If Truong et al.'s mechanism is not the correct one, what is? We have no definitive answer to this question, although magnetohydrodynamic effects appear to be a promising candidate and deserve further study.

Acknowledgments

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