Detection of Small Electrical Currents Using NMR Microscopy

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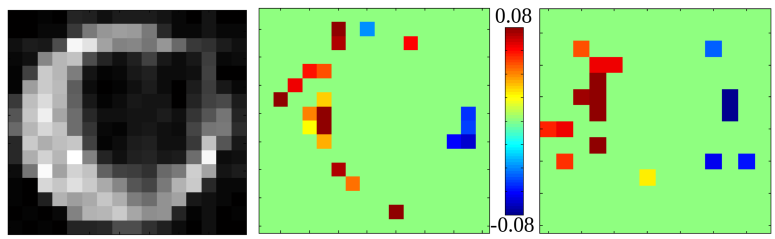
Introduction

Phase shifts in the gradient echo MRI signal caused by the presence of small currents in the sample have been suggested as a possible mechanism for direct detection of electrical activity in the brain (1). The authors noted that magnetic field strength generated by currents due to single axons firing should be on the order of 10^{-15} T, and those from spontaneous brain activities should be roughly 10^{-12} T, and that the smallest current they were able to detect directly was on the order of 10 uA, corresponding to a magnetic field of 1.7 x 10^{-9} T, or up to three orders of magnitude larger than the desired target (1). Current density mapping to study neuronal function faces another hurdle – namely the number of physiological processes that can cause phase changes in MR imaging, although work has been done to help partially alleviate this problem (2). Significantly smaller currents could potentially be detected using high-field imaging and small receiver coils. Here we present preliminary data showing detection of these currents in phantoms.

Methods

All experiments were carried out on a 17.6 T Bruker spectrometer (Bruker Biospin, Ettlingen, Germany), equipped with imaging gradients (1 T/m maximum gradient strength). Solenoidal microcoils ranging in diameter from 750 µm to 900 µm were constructed and used for RF transmission and signal detection. Currents of 25 µA, 3.4 µA, and 970 nA (DC) were conducted through a wire 75 µm in diameter immersed in water doped with 5 µM Gd-DTPA. The currents were created using a voltage generator (Conrad Electronic, Hirschau, Germany) in series with a resistor. Current/resistance for the 3.4 µA and 970 nA experiments were 39.7 V/11.5 MΩ and 14.8 V/15.2 MΩ, respectively. The 3.4 µA experiment was conducted using 3-D gradient echo, TR/TE=40/11 ms, 64 x 16 x 16 data matrix, 2.4 x 0.6 x 0.6 mm FOV (37 μm^3 voxels), 4 images per on or off period, and 128 images. The 970 nA experiments were conducted using 2-D gradient echo, TR/TE-20/11 ms, 64 x 16 data matrix, 87 μm^2 in-plane resolution, 300 µm slice thickness, 4 signal averages, 4 and 16 images per on or off period in two experiments, and 512 total images. In all cases, the sample was oriented perpendicular to the B_0. The data were processed in Matlab (The Mathworks, Natick, MA, USA). The baseline drift was removed using a cubic spline function, and the phase of the Fourier-transformed image was correlated against the boxcar function describing the applied current.



(a) (b) (c)

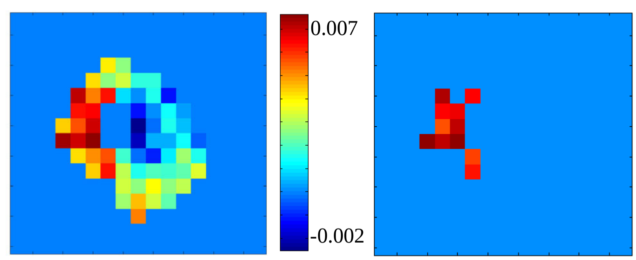
Figure 1: (a) Single slice magnitude image from 3.4 µA experiment. (b) Subtraction image, masked for noise and stimulus-correlation ($p<0.05$) for the same experiment, and (b) Simulated experiment. Scaling, in radians, is the same for (b) and (c).

Results

For the 25 and 3.4 µA experiments, subtraction images revealed dipolar phase change across the sample, with stimulus correlated pixels on both sides of the wire. Figure 1a depicts a magnitude image of a 75 µm wire in a 530 µm capillary, surrounded by gadolinium doped water. The measured phase changes in the stimulus correlated pixels ($p<0.05$) are shown in Figure 1b. A simulated experiment with the same size wire plus susceptibility artifact, offset from center, noise levels, and resolution, is shown in Figure 1c. For a 970 nA experiment, an image of the average phase during the "off" period subtracted from the average phase during the "on" period is shown in Figure 2a. Stimulus-correlated pixels ($p<0.05$) are shown in Figure 2b.

Discussion

As predicted from the Biot-Savart Law, the observed phase changes due to the current were dipolar, mutually orthogonal to the principal axes of both the B_0 and the wire. The magnitude of the measured phase changes is very close to that from simulations. The appearance of the stimulus correlated dipole for the 3.4 µA experiment is also very similar to the simulated experiment. Of some concern is the fact that in the 970 nA experiments, stimulus correlated pixels lie only on the positive side of the dipole, on which side the changes are also slightly larger than on the negative side of the dipole. We believe this most likely relates to a bias from the algorithms employed to remove the extremely complex, downward drifting phase baseline in our experiments. However, a Fourier transform of the phase time-course in a stimulus correlated pixel shows a peak at the on-off frequency for this experiment, which is not seen in an uncorrelated pixel, again indicating detection of the current induced changes for currents as low as 970 nA.



(a) (b)

Figure 2: (a) Subtraction map – average phase over all "off" images, subtracted from all "on" images (after baseline correction) for 970 nA experiment (b) The same image, masked for current correlated pixels ($p<0.05$). The scaling, in radians, is identical in both images.

Additionally, our work has revealed some possible pitfalls of such experiments. Chief among these is the fact that several experiments conducted prior to those presented here revealed a quadrupolar structure, rather than the expected dipole. Simulations (not shown here) revealed this behavior to be related to sub-pixel motion, resulting in a shifted susceptibility artifact and corresponding phase change, which mimics stimulus correlated phase change. In low-resolution experiments, it may not be possible to see this quadrupole, and since the motion is also stimulus-correlated, the interpretation of results (stimulus versus motion) may be more difficult. In our experience at 750 MHz, motion was seen when using wires smaller than 75 µm to conduct the current.

Overall, our experiments represent an order of magnitude improvement in direct MRI detection of small currents, although the end goal of detecting activation in neural tissue requires substantial further improvement in detection sensitivity.

Acknowledgments

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References

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