Detection of an Earthworm Axon Current with Simultaneous MRS

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INTRODUCTION

Direct detection of axonal neural magnetic fields (NMFs) by magnetic resonance imaging has met with conflicting evidence. Chow *et al.* reported a significant magnitude change in the human optic nerve and corpus callosum [1,2]. However, Park and Lee concluded that the modeled signal changes of axonal NMFs were negligible [3]. The objective of this study is to demonstrate the temporal signature of axonal NMFs in the free induction decay (FID), which provides the temporal resolution required to capture an axonal event. Simultaneous electrophysiology is used to time-lock earthworm action potentials to FID acquisition. The phase of the FID signal change is also simulated using an experimentally verified method for predicting the magnetic field generated by an axon [4]. Our data demonstrates clear evidence of a phase change that temporally corresponds to the electrophysiologically recorded action potential and is consistent to our theoretical predictions.

METHODS

Electrophysiology*:* Earthworm nerve cords were isolated and sustained in saline. The amplitude of the cord stimulation was held constant for each trial and was chosen to be at the threshold of action potential generation, which randomly created two groups: action potentials (AP) and no action potentials (nAP). Two recording electrodes were present at the coil entrance and exit.

FID*:* The nerve cord was positioned through a custom RF transceiver (ID = 1 mm, length = 4 mm) and perpendicular to B_0. The FID was measured with the following parameters: 90° excitation pulse, 9.4 T, 2.0 s T_R, 3.125 kHz sampling bandwidth, 163.84 ms acquisition time and 1,000 repetitions per trial. Stimulation of the nerve cord was applied during odd T_R's but not during even T_R's for control. A variable delay was placed on the RF excitation pulse in order to time-lock the calculated arrival of the action potentials to the onset of FID data acquisition. A total of 7-12 trials were repeated for each of 6 nerve cords.

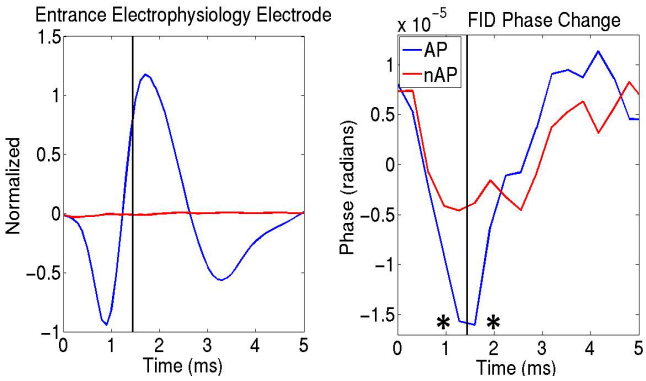

Figure 1: Average action potential recorded at the entrance of the coil (left). The average phase of the FID (right). A student t-test was performed on the phase data and astrices (*) represent time points with p<0.05. Total AP trials (blue) = 16,718, nAP (red) = 12,920. The time-axis was corrected for the arrival of the action potential at t = 0 ms for both traces. Black verticle lines represent the transition between axonal currents at t = 1.44 ms.

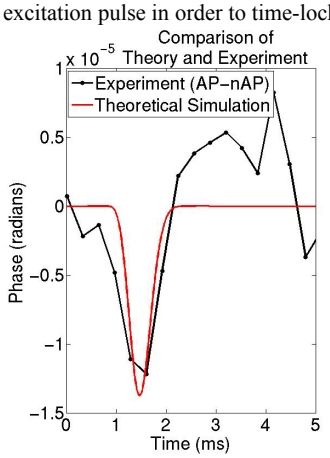

Figure 2: The signal phase was theoretically calculated (red) and compared to our experimental phase difference (black). This difference was calculated by subtracting the mean APn from the mean AP group.

FID Phase Simulation*:* The magnetic field of an action potential was calculated at increasing distances from the axon surface using the methods of Woosley, et al. (ρ = 46-350 μm, a = 45 μm, σ_i = 1.70 S/m, σ_e = 2.06 S/m, u = 16.5 m/s) [4] and extended to include the length of our RF coil. The FID signal phase change that results from this magnetic field was then calculated using the equation below:

$$\boldsymbol{\phi(t) = \int \gamma \cdot \frac{1}{\pi r^2 l} \iiint r \cdot B(r,\theta,l)\, dr\, d\theta\, dl\, dt}$$

RESULTS AND DISCUSSION

A difference in phase between AP and nAP FIDs is observed and two of the time points show statistical significance (Fig. 1). The experimental phase change is consistent with the change predicted by our theoretical simulation (Fig. 2). The signal phase decreases during the initial depolarizing component of the action current and promptly returns to baseline during the subsequent repolarizing component. This transition between these two currents in the electrophysiological data corresponds to the peak of the FID phase and is represented by the black vertical line in figure 1. The FID magnitude change did not exhibit a consistent pattern between the 6 nerve cords (data not shown). This observation could be due to variable local field inhomogeneities experienced by the different cords that were too small to be shimmed effectively.

CONCLUSIONS

A significant signal change is recorded in the phase of the FID that corresponds to the electrophysiological data and axonal magnetic field simulation. The signal change was shown to return to zero, suggesting that a greater temporal resolution is required in order to capture an axonal event than what is typically used in fMRI.

REFERENCES

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ACKNOWLEDGEMENTS

This research is partly funded by the Emory University PRISM Fellowship and the GK-12 program of the NSF, Award #DGE0536941.