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Effect of Peripheral Nerve Action Currents on Magnetic Resonance Imaging

Ranjith Wijesinghe, *Member, IEEE,* and Bradley J. Roth

Abstract— **Many researchers have attempted to detect neural currents directly using magnetic resonance imaging (MRI). The action currents of a peripheral nerve create their own magnetic field that can cause the phase of the spins to change. Our goal in this paper is to use the measured magnetic field of a nerve to estimate the resulting phase shift in the magnetic resonance signal. We examine three cases: the squid giant axon, the frog sciatic nerve, and the human median nerve. In each case, the phase shift is much less than one degree, and will be very difficult to measure with current technology.**

I. INTRODUCTION

Many researchers have attempted to detect neural currents directly using magnetic resonance imaging (MRI) [2, 4, 9, 11, 14]. The action currents of a nerve create their own magnetic field [17, 21] that can act like a gradient field during magnetic resonance imaging, causing the frequency or phase of the nuclear spins to change because of the presence of the action current. However, this magnetic field is very small, and it is not clear if this effect will be measurable. Our goal in this paper is to use the measured magnetic field of a peripheral nerve to estimate the resulting phase shift in the magnetic resonance signal.

Magnetic measurement of action currents using magnetic resonance would be important because it would allow true functional imaging of action currents using all the power and resolution of MRI. Researchers have developed functional MRI to detect brain activity, which measures the blood oxygenation level-dependent (BOLD) signal [13]. However, BOLD is an indirect measurement of perfusion rather than a direct detection of neural activity. Ideally, measurement of the magnetic field of action currents would provide a signal that better follows the spatial and temporal distribution of neural activity. Biomagnetic measurements using magnetometers outside the body have been used to measure neural activity directly [5, 8, 15]. However, MRI measurements would detect the magnetic field inside the body, eliminating the ill-posed and difficult inverse problem that normally plagues biomagentic studies. For this reason, magnetic resonance detection of action currents has generated much interest in the past few years.

Previous studies have attempted to calculate the magnetic field associated with action currents from first principles [3, 14]. However, a large body of research exists in which magnetic fields of nerves, and even single axons were directly measured using ferrite-core, wire-wound toroids [6]. Our goal is to use these measurements to estimate the MRI signal caused by action currents.

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Ranjith S. Wijesinghe is with the Department of Physics and Astronomy, Ball State University, Muncie, Indiana (phone: 765-285-8811; Fax 765-285-5674; rswijesinghe@bsu.edu).

Bradley J. Roth is with the Department of Physics, Oakland University, Rochester, Michigan (roth@oakland.edu).

II. METHODS

Action currents in nerves have been directly measured using toroidal pickup probes by us and our former colleagues [7, 19, 20, 22]. From these measurements of the current, I, and the radius of the fiber, r, we can calculate the magnetic field created by this current at the surface of the fiber using the Ampere's law,

$$B = \frac{\mu_0 I}{2\pi r}. \qquad (1)$$

where μ_0 is the magnetic permeability of free space.

In the magnetic resonance signal, this magnetic field will induce a phase shift, ϕ, of

$$\phi = \gamma B \Delta t. \qquad (2)$$

where γ is the gyromagnetic ratio of a proton, (2.7×10^8 $s^{-1}T^{-1}$), B is the strength of the magnetic field created by the nerve, and Δt is the duration of the rising phase of the magnetic field. This phase shift is an invaluable tool to investigate whether a noticeable event occurs in the MR signal due to action currents in nerves.

III. RESULTS

We have investigated the phase shifts due to four different measured action currents, from the squid giant axon, the frog sciatic nerve, and the human median nerve.

1) Squid Giant Axon

The squid axon is historically one of the most important bioelectric systems studied [10], and is one of the largest single axons known. Wikswo and van Egeraat [20] measured the action current associated with a propagating action potential along a squid giant axon, and obtained I = 6 μA. Hodgkin and Huxley [10] reported that the radius of the squid giant axon, r, was about 0.5 mm. Thus, the calculated value of B at the surface of the axon, from Eq. 1, is 2.4 nT. The rise time is approximately 0.4 ms, so the induced phase shift, from Eq. 2, is about 0.00026 radians, or 0.015°.

2) Frog Sciatic Nerve

The frog sciatic nerve consists of thousands of individual small axons. Wijesinghe and colleagues [19] measured the action current when a strong stimulus excites most of these axons, and found I = 0.2 μA and r = 0.75 mm. Thus, B is 0.05 nT. The rise time is 1 ms, so the induced phase shift is about 0.0007°.

3) Human Median Nerve

The first intraoperative recording of the action current of the human median nerve bundle was reported by Wikswo et al. (1990) using an openable, toroidal pickup coil. They found the current to be $I = 0.35\ \mu$A. The radius of the median nerve bundle is $r = 2$ mm. Therefore, the corresponding magnetic field at the surface of the bundle is 0.035 nT. The rise time is about 0.75 ms. Therefore, the calculated phase shift is about 0.0004°.

All these phase shifts are very small; much less than one degree.

IV. DISCUSSION

We found that in four common bioelectric systems, the phase shift induced during MRI is small (often less than one tenth of a degree), and would probably not be measurable with current technology. Therefore, we are not optimistic about the future of such techniques. In fact, we believe our results above overestimate the MRI signal for the following reasons. 1) The magnetic field of an action potential consists of a biphasic signal with both depolarization and repolarization signals. The repolarization current lasts somewhat longer than the depolarization current, but is also weaker, so the integrated phases from depolarization and repolarization have the same magnitude but opposite sign. Thus, the net signal of the action current is nearly zero, as the phase shifts of depolarization and repolarization cancel. The entire action potential is over in just a few milliseconds, which is a short time compared to most MRI imaging pulse sequences. Thus, action potentials will be more difficult to detect than predicted above, unless very brief, carefully timed pulse sequences are developed. 2) In the case of the nerve, the action potentials in different axons propagate at different speeds, so that the compound action potential results from the summation of many single axon signals [19]. Therefore, the measured signal will decrease as the action potentials propagate and become less well synchronized. 3) We calculate the magnetic field just outside a nerve, where it is largest. In general, the field will fall off with distance outside the fiber (Eq. 1). A typical MRI signal represents an average over a pixel or voxel, which often has a size on the order of a millimeter. Thus, only part of a voxel may experience a large magnetic field, with other parts experiencing a weaker field. 4) In most cases, the entire nerve will not be simultaneously active. Whereas for a frog sciatic nerve it is fairly easy to stimulate most or all of the axons using a strong electrical pulse, in an experiment on a human median nerve under normal physiological conditions only a small fraction of the axons in a nerve will be active. We can confirm this fact by comparing the data presented in this paper for the frog sciatic nerve bundle and the human median nerve. Even though the radius of the human median nerve is much larger that that of sciatic nerve, the current recorded in the human median nerve is much smaller than that of the frog sciatic nerve. This proves that the active fibers in the human median nerve bundle are fewer than that in the frog sciatic nerve bundle. For these reasons, we suspect that detecting neural activity will be even more difficult than our calculated phase shifts suggest.

Troung and Song [18] recently introduced another method called "Lorentz Effect Imaging" for detection of action currents using MRI. This method is based on the principle that when a current is placed in a magnetic field, there exists a force--the Lorentz force--on the current. This Lorentz force will cause a current-carrying nerve to shift from its original position in the body. If there simultaneously exists a magnetic field gradient during the MRI, this movement of the axon causes the spins to diphase, resulting in an artifact in the magnetic resonance signal. Roth and Basser [16] recently investigated this effect using a mathematical model and found that the Lorentz displacement was too small to be detected using MRI techniques. In fact, they concluded that the Lorentz force effect will be even smaller than the effect examined in this paper.

Our estimates of the fractional change in magnetic field strength or frequency caused by action currents assumes that the magnetic resonance study is performed using a typical static magnetic field strength on the order of 1 T. However, action currents might be detected more easily using ultra-low field MRI systems [4, 12]. The ability of these systems to detect biomagnetic signals is yet to be explored on living tissues. Because the biomagnetic field is not proportional to the static magnetic field (as it would be for chemical shift or susceptibility effects), a lower static field means a larger fractional change in frequency caused by action currents. Thus, ultra-low field measurements may be one way to better detect action currents.

V. CONCLUSION

We find that MRI measurements of action current in nerve are unlikely using current technology. Bandettini et al. [1] asked if detecting neural activity using MRI is "fantasy, possibility, or reality?" Our results suggest that, at least for peripheral nerves, "fantasy" may be closer than "reality".

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