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An open-source hardware and software system for acquisition and real-time processing of electrophysiology during high field MRI

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ABSTRACT

Simultaneous recording of electrophysiology and functional magnetic resonance imaging (fMRI) is a technique of growing importance in neuroscience. Rapidly evolving clinical and scientific requirements have created a need for hardware and software that can be customized for specific applications. Hardware may require customization to enable a variety of recording types (e.g., electroencephalogram, local field potentials, or multi-unit activity) while meeting the stringent and costly requirements of MRI safety and compatibility. Real-time signal processing tools are an enabling technology for studies of learning, attention, sleep, epilepsy, neurofeedback, and neuropharmacology, yet real-time signal processing tools are difficult to develop. We describe an open-source system for simultaneous electrophysiology and fMRI featuring low-noise (<0.6 μV p–p input noise), electromagnetic compatibility for MRI (tested up to 7 T), and user-programmable real-time signal processing. The hardware distribution provides the complete specifications required to build an MRI-compatible electrophysiological data acquisition system, including circuit schematics, print circuit board (PCB) layouts, Gerber files for PCB fabrication and robotic assembly, a bill of materials with part numbers, data sheets, and vendor information, and test procedures. The software facilitates rapid implementation of real-time signal processing algorithms. This system has been used in human EEG/fMRI studies at 3 and 7 T examining the auditory system, visual system, sleep physiology, and anesthesia, as well as in intracranial electrophysiological studies of the non-human primate visual system during 3 T fMRI, and in human hyperbaric physiology studies at depths of up to 300 feet below sea level.

1. Introduction

Simultaneous recording of electrophysiology during functional magnetic resonance imaging (fMRI) is a technique of increasing importance in brain imaging research. Commercial solutions exist for data acquisition and analysis of these data, but with the rapid development of new neuroscience and clinical applications, there is a growing need for end-user customization of both hardware and software for data acquisition and real-time processing. In many studies, hardware customization may be necessary to meet application-specific requirements for acquisition bandwidth, number of channels, amplifier configurations, and other hardware design specifications. Software customization is also an important feature for many applications, particularly for those that require real-time processing of acquired data. For studies examining epilepsy, sleep, or drug effects, for example, the ability to observe the study subject's electrophysiological state in real-time is essential for success (e.g., epileptic spiking activity, sleep stage, etc.) (Lemieux et al., 2001; Portas et al., 2000; Schomer et al., 2000). Such real-time observations would allow the investigator to be certain that an adequate amount of data are being recorded in each desired electrophysiological state during an experiment. ERP studies conducted simultaneously with fMRI would benefit in a similar way from real-time processing, since the duration of a scan could be adjusted to ensure that an adequate number of trials were observed. Real-time processing is also required for biofeedback studies, where study subjects must be able to observe, with minimal delay, their own electrophysiological state to permit feedback control (Basmajian, 1981; Delorme and Makeig, 2003; Fox, 1979; Herrmann et al., 2004; Hill and Raab, 2005; Riddle and Baker, 2005; Sinkjaer et al., 2003).

Instrument design for electrophysiological recording during MRI is difficult due to the presence of the large static and gradient magnetic fields, and radiofrequency fields, each of which introduces

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Table 1
MRI Safety: Potential adverse interactions between a MRI environment and a medical device

Imaging field	Physical effect	Potential complications
Static magnetic field	Eddy currents	Tearing of tissues during patient insertion
	Acceleration due to magnetic force	Serious injuries or death due to “missile effect”
	Electrodes perturb field homogeneity	Image artifact and/or distortion
Gradient magnetic field	Faraday’s induced currents (dB/dt)	Painful peripheral nerve stimulation
		Device malfunction or failure
Radio frequency field	RF power deposition on tissues	Excess tissue heating or burns
	Device induced EM interference	Noise in MR images
	Leads perturb RF field	Poor image SNR

potential complications for safety, instrument function, and image quality (United States Food and Drug Administration, 1997; Huang-Hellinger et al., 1995; Ives et al., 1993; Lemieux et al., 1997; Chen, 2001; Bonmassar et al., 2001; Angelone et al., 2004, 2006; Vasios et al., 2006). These complications are summarized in Table 1. Hard-to-find non-ferromagnetic components must be used throughout the design to minimize complications from the static magnetic field. Print circuit boards (PCBs) must be designed to minimize pickup of gradient artifacts and transmission of RF interference, and electrodes and electrode leads must be made with special materials to prevent RF heating and minimize susceptibility artifacts (Vasios et al., 2006). A number of strategies exist for removing the magnetic gradient artifact, ranging from subtraction of a template waveform (Allen et al., 2000; Niazy et al., 2005) to synchronization of the electrophysiological sampling with gradient switching (Goldman et al., 2000; Anami et al., 2003; Mandelkow et al., 2006). In all cases, the dynamic range of the instrument must be large enough to record the gradient artifact without saturation or distortion. Ballistocardiogram artifacts, EEG artifacts induced by cardiopusatile motion within the static magnetic field, remain a problem, and can be removed with post-processing methods (Allen et al., 1998; Bonmassar et al., 2002; Niazy et al., 2005) or reduced in amplitude by using specially designed EEG electrodes (Vasios et al., 2006) or head restraint methods (Anami et al., 2003). Table 2 summarizes additional performance characteristics that are needed for electrophysiological recording within the MRI environment. Development of data acquisition and real-time processing software is also challenging, since the software must interact at a low-level with hardware and hardware drivers, and work quickly enough to keep up with acquired data, while maintaining high-level functionality for ease of use and customization.

One way to facilitate hardware and software customization and development would be to make the hardware and software freely available in an open-source fashion. For software, the open-source model has been extremely successful by facilitating collaboration between large groups of researchers and developers, with few requirements for success beyond a computer and programming knowledge. With hardware, the analogous open-source concept is more challenging. While it is easy to distribute and modify circuit schematics, if the hardware are sufficiently complex, the ability to reduce the design to practice, through multiple design and construction steps (circuit, PCB, components, etc.) becomes a limiting factor. Ongoing developments in electronics construction technology, such as 3D printers and circuit printers, are reducing these limitations by allowing automated construction of electronic circuits and systems based on construction files (e.g., Gerber files, robotic assembly files) that fully specify the system (Chalamala and Temple, 2005; Mei et al., 2005; Mikhak et al., 2002). To make open-source hardware reducible to practice in the way that open-source software is, open-source hardware would need to include not only schematics for the circuit designs, but also an integrated library of construction files that would allow end-users to construct the hardware using largely automated methods, and a means to compile these files in an organized way with successive design changes.

In this paper we describe an open-source hardware and software system for acquisition and real-time processing of electrophysiology during high-field MRI (up to 7 T). We have named this system “High Field One” (HF-1). A novel aspect of this work is that all elements of the system have been gathered together into a comprehensive, freely available open-source distribution. The hardware has been designed to minimize electromagnetic interference (EMI) between the data acquisition device and the MRI, and features EMI-reducing PCB designs, double shielding, and low input noise. The hardware distribution includes all circuit and PCB design files, a bill of materials and data sheets for all components, including difficult to find non-ferrous connectors and parts, construction files for automated assembly, and test procedures, compiled together to promote rapid and organized development. The software distribution includes data acquisition software from high-level LabView virtual instruments (VIs) down to low-level firmware, as well as high-level real-time processing functions implemented in LabView. This open-source system will allow end-users to build an MRI-compatible electrophysiological acquisition system, with the ability to modify the design to their individual specifications, and to

Table 2
Specifications for recording electrophysiology during MRI

	MRI standard	Specification in HF-1
Field strength	1.5 T	7 T
DAC resolution	16 bits	24 bits
Input signal range	±20 to 30 mV	−176 to +174 mV
LSB resolution	0.30–0.46 μV nominal	0.024 μV nominal
Scanner synchronization	NO	YES
External clock	NO	YES
Real-time processing	NO	YES
End-user customization	NO	Open-source hardware and software
Bandwidth	0.1–70 Hz	DC to 4 kHz
Shielding	Faraday shield	Double-shielding
Electrode heating protection	15 kΩ discrete resistors	Ink Cap (resistive leads reduce SAR)
Electrode artifacts	AgCl electrodes	Ink Cap (AgCl ink reduces susceptibility artifacts)