Characterization of a Graphene-Based Electrophysiology Probe for Concurrent EEG-fMRI

Suchit Kumar[1], Samuel M. Flaherty[2], Alejandro Labastida-Ramírez[2], Anton Guimerà Brunet[3], Ben Dickie[4], Kostas Kostarelos[2], Rob C. Wykes[1,2], Louis Lemieux[1*]

[1]University College London Queen Square Institute of Neurology, London, UK

[2]Centre for Nanotechnology in Medicine & Division Neuroscience, University of Manchester, UK

[3]Centro de Investigación Biomédica en Red en Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Madrid, Spain

[4]Division of Informatics, Imaging and Data Sciences, University of Manchester, Manchester, UK

Abstract

EEG-fMRI (electroencephalography; functional magnetic resonance imaging) is a powerful technique for synchronously recording brain electrical activity and hemodynamic changes in both normal and pathological states. However, current methodologies face challenges, such as metallic artifacts from conventional EEG electrodes leading to MRI image distortions and signal loss, and safety concerns related to RF heating and mechanical forces in the MRI environment. This project explores the use of graphene-based electrophysiology probes (Graphene Solution-Gated Field-Effect Transistors, or gSGFET) as a solution to these issues [1]. These probes minimize metallic interference with MRI and offer high-fidelity, DC-coupled brain signal recording [2].

Our objectives include validating the MR localization and compatibility of the probes, assessing their ability to visualize MRI biomarkers of epilepsy, demonstrating their functionality in concurrent electrophysiological and fMRI measurements, and developing a clinical version of the probes for human use.

We performed electromagnetic (EM) simulations using the finite-difference time-domain (FDTD) method in Sim4Life on a 3D rodent model [3, 4]. The RF coil setup involved a quadrature birdcage design, while a 3D model of the graphene-based EEG probes was created from 2D drawings (Fig. 1). Results from the simulations indicated a 15-20% increase in B_1^+ and E-field magnitudes near the probes (Fig. 2) and a rise in the mean mass-averaged specific absorption rate (SAR) from 0.63 W/kg (without probe) to 0.83 W/kg (with probe), with peak SAR localized in the skin (Fig. 3).

Initial ex vivo phantom and in vivo rodent experiments demonstrated promising results, including artifact-free MR images and stable performance of the graphene probes during functional tests (Fig. 4). Future work will focus on conducting concurrent EEG-fMRI studies in chronically epileptic rodents and optimizing the probes for human application. This study confirms the potential of graphene-based EEG probes for safe and effective integration into MRI environments [5], paving the way for enhanced brain imaging techniques.

Acknowledgements: This project is funded by the EPSRC under grant no. EP/X013669/1. The authors are grateful for the support from Sim4life, ZMT for providing the science license.

References: [1] Bonaccini Calia, Andrea, et al. Nature Nanotechnology 17.3 (2022): 301-309. [2] Wykes, Rob C., et al. Clinical and Translational Medicine 12.7 (2022): 1-4. [3] Sim4Life, ZMT, <http://www.zurichmedtech.com>. [4] Kainz, Wolfgang, et al. Physics in Medicine & Biology 51.20 (2006): 5211. [5] International Electrotechnical Commission (IEC) (2022): IEC 60601-2-33.

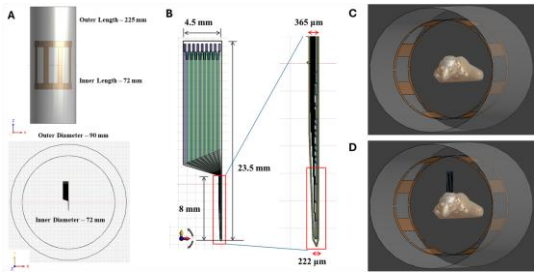

***Fig. 1**. (A) Transmit highpass birdcage RF coil dimensions; (B) 16-channel intracortical graphene probe dimensions; (C) Configuration of rodent model placed in RF coil without, and (D) with graphene-based probe model as a brain implant.*

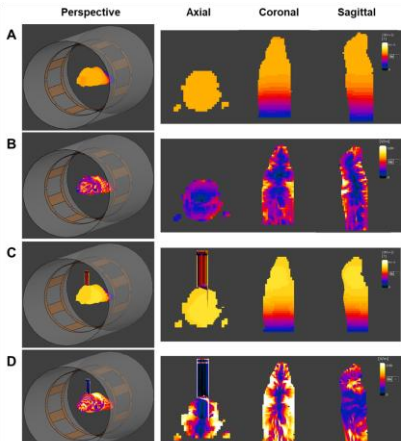

***Fig. 2.** Simulated B_1^+-field distribution in rodent model (A) without, (C) with probe model; E-field distribution in rodent model (B) without, (D) with probe model.*

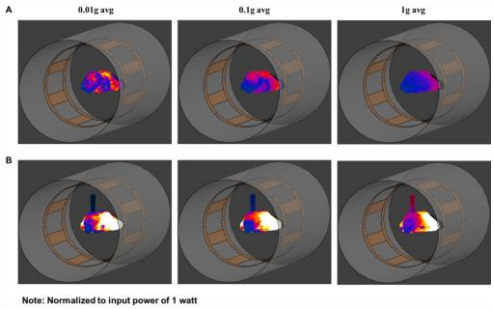

***Fig. 3**. Simulated mass-avg SAR distribution in rodent model (A) without, (B) with EEG probe model for 0.01g, 0.1g and 1g tissue mass.*

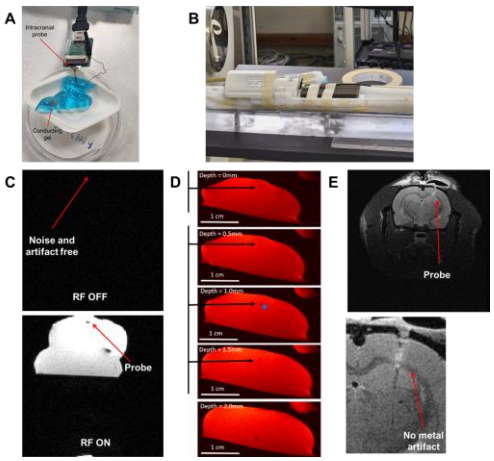

***Fig. 4.** (A, B). Experimental setup of the graphene gSGFET in MRI; (C, D, E). MRI artifact study in ex vivo phantom with epicortical, & intracortical probes, and in vivo (rat) with intracortical gSGFET array.*