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 Bioingenieria, Biomateriales y Nanomedicina (CIBER-BBN), Madrid, Spain
[4]Division of Informatics, Imaging and Data Sciences, University of Manchester, Manchester, UK

Introduction

Graphene-Based Recording Technology

- New advancements in electrophysiological recording technology, specifically Graphene Solution-Gated Field-Effect Transistors (gSGFET) [1].
- gSGFETs offer several advantages over traditional electrodes, particularly in MRI settings.

Advantages of gSGFET

- Reduced Metal Interference: Significantly lowers the amount of metal that can interfere with MRI scans.
- High-Fidelity Brain Signal Recording: Enables DC-coupled brain signal recording with high fidelity, specifically demonstrated in rodent models [2].

Importance of MRI Compatibility

- Interest in performing MRI acquisitions on animals implanted with gSGFET probes.
- Ensuring MR compatibility and safety of these graphene-based EEG probes is crucial for research continuity and accuracy.

Study Objectives

- Computational Simulations: Conducted to assess the electromagnetic (EM) interaction and safety of animals implanted with these probes within an MRI environment.
- MRI Experiments: Conducted to verify MRI compatibility and localization in both ex vivo and in vivo conditions.
- Goal: Achieving the highest possible level of MR compatibility for these advanced probes.

Methods

- **EM Simulation Analysis**
  - Software: Sim4Life (V8.0, ZMT) using Finite-Difference Time-Domain (FDTD) solver.
  - Model: 3D rodent model comprising 68 tissues [3, 4].
- **RF Transmission Coil Setup and Specifications**
  - Type: Quadrature highpass birdcage RF coil.
  - Coil dimensions: Diameter: 72 mm, Length: 72 mm.
  - Shield dimensions: Diameter: 90 mm, Length: 225 mm.
  - Coil structure: 8 rungs, each 9.9 mm wide.
  - Tuning capacitor: 14.2 pF placed on the end-rings, which are 11.5 mm wide. *See* ***figure 1***.
- **Simulation Setup**
  - Excitation parameters: 300 MHz Gaussian excitation with a bandwidth of 650 MHz, excited in two-port, combined in circular-polarized mode.
  - Sub-gridding feature: Utilized for localized mesh refinement, obtained from ZMT.
- **SAR Calculation**
  - Specific Absorption Rate (SAR): Mean and peak SAR averaged over 0.01g, 0.1g, and 1g tissue-mass were calculated following IEC guidelines [5].
- **MRI Experiments**
  - 7 T Bruker MRI
  - Ex vivo/ In vivo Sequence Parameters: Axial T2 TurboRARE, FOV: 35 x 35 x 15 mm, matrix = 512 x 512 x 30, TE = 33 ms, TR = 3192 ms, NEX = 5, RARE factor = 8

Results & Conclusions

Results

- **B_1^+-Field and E-Field Distributions:**
  - B_1^+ and E-field magnitudes increased by approximately 15-20% near the probes.
  - Cause: Induced current in the metal layers of the probes during transmission (see ***figure 2***).
- **SAR Distributions:**
  - Elevated SAR due to probes:
    - Mean Mass-Averaged SAR (W/kg): **Without probe**: 0.63; **With probe**: 0.83
    - Peak Mass-Averaged SAR (W/kg): **Without probe**: 0.01g: 2.5, 0.1g: 1.3, 1g: 0.8
      With probe: 0.01g: 5.9, 0.1g: 2.8, 1g: 1.6 (see ***figure 3***).
  - Localization: SAR peak localized in the skin.
- **Computational Time:**
  - **With probe**: Approximately 160 h / port; **Without probe**: Approximately 1.5 h / port.
  - Note: Computational power limitations on a single GPU require cluster GPU implementation.
- **MRI findings:**
  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 **(see *figure 4*).**

Conclusions

- **EM Interaction:** Successfully demonstrated the EM interaction of graphene-based EEG probes in an MRI environment.
- **RF Transmission and SAR:** Graphene-based probes can affect RF transmission and increase SAR deposition while staying within permissible limits, ensuring MR compatibility and safety.
- This study confirms the potential of graphene-based EEG probes for safe and effective integration into MRI environments.
- **Future Work:**
  - Optimization: Further work needed to optimize computational efficiency using GPU clusters.
  - Concurrent Studies: EEG-fMRI studies in vivo in normal and chronically epileptic rodents.
  - Scaling: Potential scaling of these probes for human application.

Figures

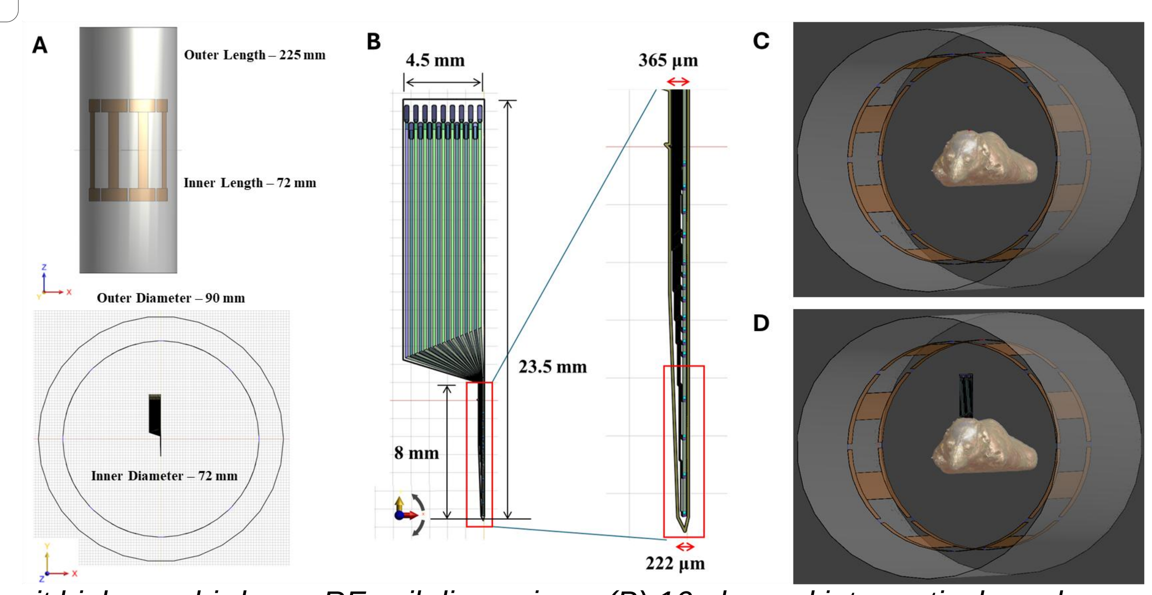

Fig. 1. *((A) Transmit highpass birdcage RF coil dimensions; (B) 16-channel intracortical graphene probe dimensions; (C) Configuration of rodent model placed in RF coil without, and (D) with graphene-based probe model as a brain implant.*

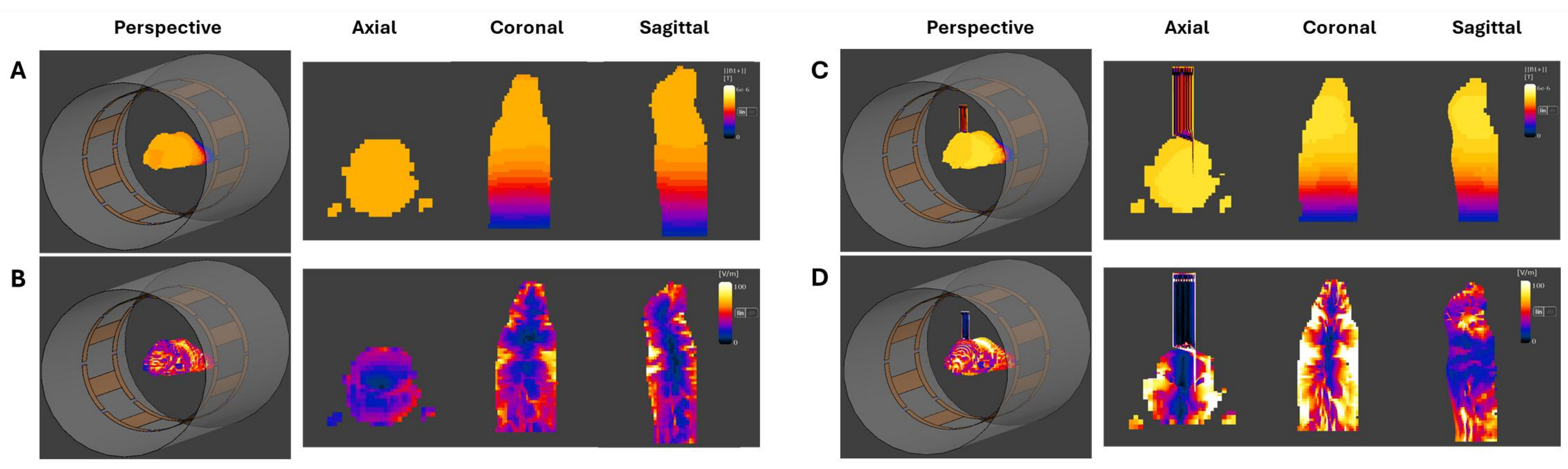

Fig. 2. *Simulated B_1^+-field distribution in rodent model (A) without, (C) with probe model; E-field distribution in rodent model (B) without, (D) with probe model.*

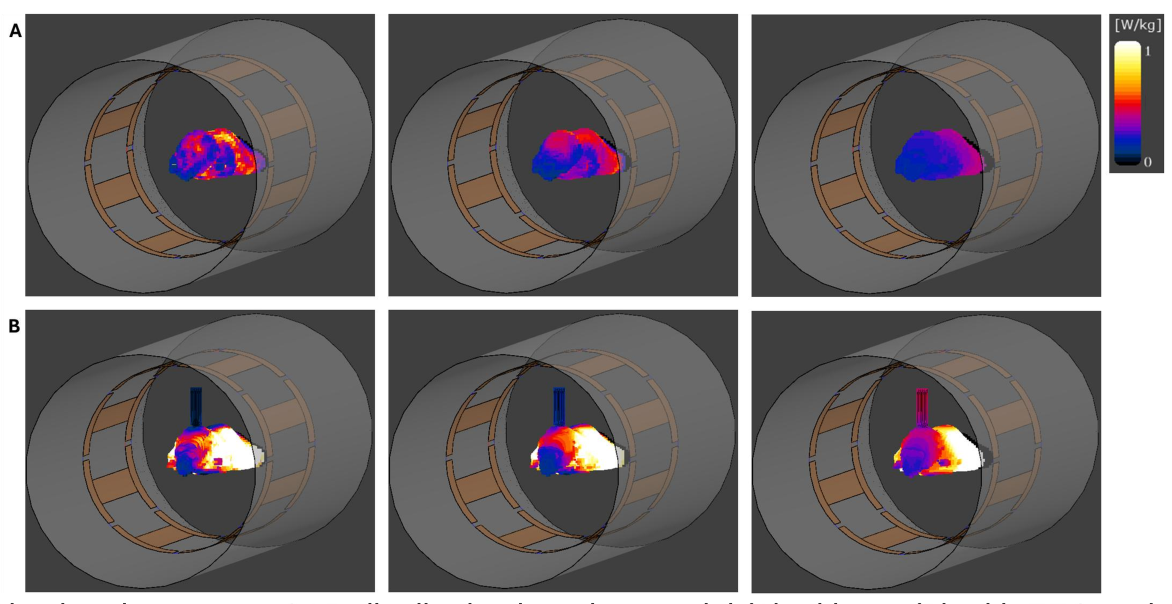

Fig. 3. *Simulated mass-avg SAR distribution in rodent model (A) without, (B) with EEG probe model for 0.01g (left), 0.1g (middle) and 1g (right) tissue mass.*

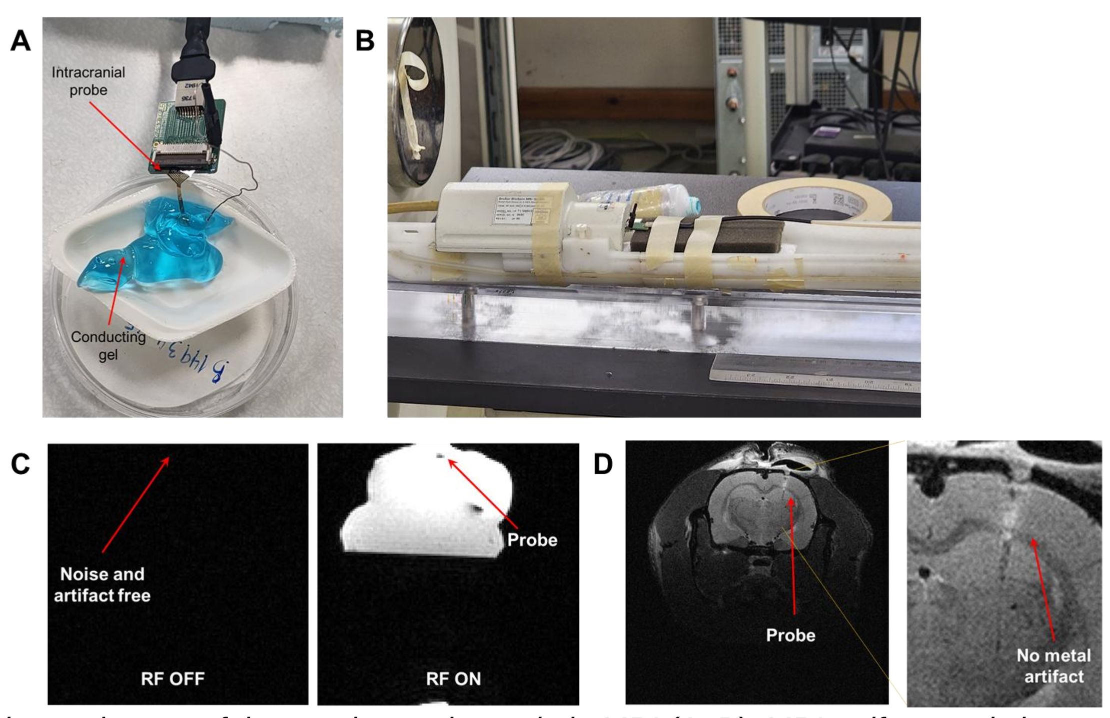

Fig. 4. *Experimental setup of the graphene electrode in MRI (A, B); MRI artifact study in ex vivo phantom with epicortical array (C), and in vivo mice with intracortical electrode array (D).*

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.

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