Fully customizable and MR-compatible dry MXene EEG system for clinical and mobile applications

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Synopsis

Understanding brain function in real-world environments requires neurotechnology that is both high-fidelity and unobtrusive. Conventional EEG utilizes gelled electrodes, which present limitations in stability, usability, and comfort, particularly in long-term or mobile applications. We present a novel dry EEG technology enabled by $Ti_3C_2T_x$ MXene. These electrodes are soft, porous, low-impedance, and fabricated via scalable methods. We show that the electrochemical properties are non-inferior to gelled electrodes. Initial results suggest that dry MXene EEG achieves signal quality comparable to gelled electrodes, stable multi-hour recordings, and robust task specific neural features. Furthermore, these electrodes are safe and compatible with MRI–EEG applications.

Background

EEG is extensively utilized for neurodiagnostics and research in universities and clinics around the world. Despite its prevalence, EEG technology has remained largely unchanged, with few technological advances over the last several decades. Conventional scalp EEG systems based on silver/silver-chloride (Ag/AgCl) electrodes present significant limitations that restrict widespread adoption in community settings. Mounting these electrodes requires a conductive gel to reduce and maintain low enough skin-electrode impedance. This process is time-consuming and necessitates skilled technicians, which are not available outside major healthcare institutions typically in urban areas. Furthermore, these gels can irritate the skin, are difficult to clean, and cause impedance fluctuations as they dry (Drees et al., 2016). Dry electrodes have emerged as a promising solution. However, these systems often suffer from higher impedance values relative to gelled electrodes that are compensated by a larger footprint and higher mechanical pressure to maintain scalp contact, thus sacrificing spatial resolution and comfort (Hinrichs et al., 2020). Other approaches using printed conductive hydrogels and composites are not suitable for hair-dense regions (Tian et al., 2019). To address these challenges, here we introduce dry electrodes engineered from $Ti_3C_2T_x$ MXene. MXene is a highly conductive, water-based, weakly paramagnetic, and biocompatible nanomaterial uniquely positioned for bioelectrical interfacing (Garg and Vitale, 2023). These dry electrodes exhibit low impedance, high signal quality, long-term stability, and rapid setup, even across diverse hair types. Importantly, they are suitable for integration into conventional cap designs and commercial EEG amplifiers. In prior work, we established that $Ti_3C_2T_x$ MXene is MR-safe and compatible, with magnetic susceptibility closer to human tissues than metals (Driscoll et al., 2021). We now present preliminary data comparing dry MXene full-scalp and reduced-montage headsets against commercial gelled electrodes across cognitive tasks and multimodal recording contexts.

Methods

Dry MXene electrodes are produced by dip-coating 8 mm diameter polyvinyl acetate foam disks in an aqueous dispersion of $Ti_3C_2T_x$ MXene (20 mg/mL). Due to the hydrophilic and porous nature,

the substrates expand vertically (8 mm) upon infusion. After air drying at room temperature for 45 minutes, Ag/AgCl button snap connectors are attached using silver epoxy and cured for 10 minutes at 60 °C, supporting rapid high-throughput manufacturing (<1 hour for 10 electrodes). We measured the impedance modulus and phase spectra in a three-electrode configuration on a conductive agarose phantom (0.6% w/w agarose and 0.3% w/w NaCl) and human participants in the 1 Hz–1 MHz frequency range with a 10 mV_{RMS} input. We integrated dry MXene electrodes into a custom 10-20 headset with 21 electrodes placed at defined cranial landmarks. We also designed a reduced-montage headband consisting of 8 electrodes placed along the scalp circumference **(Figure 1)**. Both headsets are fabricated from flexible elastic fabric and incorporate adjustable bands and 3D-printed electrode holders to ensure secure contact, even during movement **(Figure 1A)**. This design allows easy adjustment and replacement of the electrodes and compatibility with MRI-safe snap-connectors. In human validation studies, dry MXene electrodes used a simplified skin preparation with an alcohol wipe and 1 mL saline application, whereas Ag/AgCl electrodes followed standard abrasive, gel-based preparation and fixation protocols. EEG was recorded with a Bittium NeurOne system at 5 kHz. To assess the safety and feasibility of high-quality EEG acquisition during MRI, a head-shaped phantom fitted with a 32-channel MR-safe EEG cap was scanned on a 3T system at the Hospital of the University of Pennsylvania **(Figure 2)**. Dry MXene electrodes were placed at 4 selected sites, with gelled Ag/AgCl electrodes occupying the remaining positions. Fiber-optic probes placed between the electrodes and phantom monitored temperature. The preparation and setup matched those used in subsequent testing on a healthy volunteer, with EEG recorded via an MRI-compatible amplifier during 5 structural and functional imaging sequences and filtered in EEGLAB (fMRIb plugin) to remove MR-related gradient and ballistocardiogram artifacts.

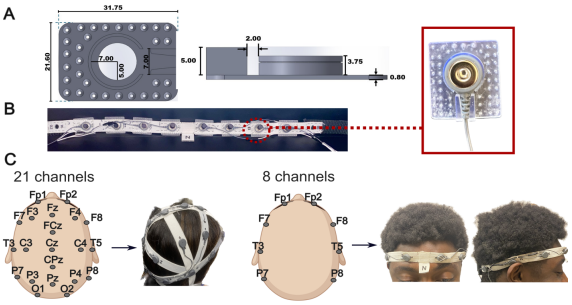

Figure 1. (A) 3D-printed holders. **(B)** Headset with dry MXene electrodes inserted. **(C)** 21 and 8 electrode montages.

Results

Impedance recorded from 3 healthy participants at Fp1 (non-hairy) and T8 (hairy) showed a mean electrode-scalp modulus of 2.1 ± 1.8 kΩ at 10 Hz, well below the clinical threshold of 10 kΩ (Shankar et al., 2026). Phantom-based measurements (n=10) further demonstrated minimal phase distortion (<5°), vastly outperforming commercial dry electrodes (ANT Neuro; ~30× higher impedance, -65°) and clinical-grade gelled electrodes (Natus; equivalent impedance $p_{TOST} < 0.05$, -20°). To validate the dry MXene headset, resting state and cognitive task paradigms were conducted in 5 participants. Pairwise Pearson correlations with adjacent Ag/AgCl electrodes indicated high signal fidelity across scalp regions (Fp1: 0.895 ± 0.059, C3: 0.929 ± 0.047, O2: 0.989 ± 0.011) and during steady-state visual evoked potential stimulation, the expected increase in SNR at the stimulus frequency was significant (paired t test, p = 0.01 ± 0.01)(Shankar et al., 2026). Safety and signal integrity were further evaluated during simultaneous MRI–EEG on a phantom and single volunteer. Over 30 minutes of scanning, dry MXene electrodes exhibited no RF- or gradient-induced heating (<1 °C) **(Figure 2D)**. No observable image distortion was present, preserving accurate anatomical structure delineation **(Figure 2F)**. EEG recorded during an EP2D BOLD fMRI sequence remained visually comparable to corresponding contralateral gelled sites after artifact removal **(Figure 2E)**.

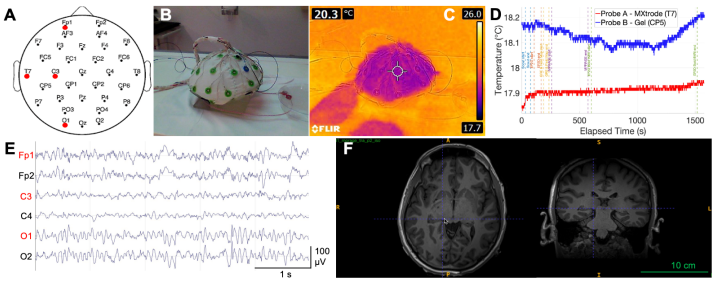

Figure 2. (A) Montage schematic. Red dots mark MXene electrode locations. **(B)** Photograph and **(C)** thermal image taken after scanning. **(D)** Temperature at a gelled (blue) and MXene (red) electrode. Dashed lines designate MRI sequences. **(E)** Representative 5 s of EEG recorded from MXene and gelled sites. **(F)** T1-MPRAGE structural MRI showing lack of image artifacts.

Discussion

This work overcomes significant technical and clinical challenges inherent to current EEG by leveraging the unique properties of MXene nanomaterials, minimized preparation time, and scalable fabrication. Prior human studies published in our recent work (Shankar et al., 2026) show that dry MXene EEG records electrophysiological markers from individuals with epilepsy, deemed clinically interpretable by board-certified neurologists. That investigation also established stable signal quality across dynamic conditions (sitting, standing, walking), extended wear (>4 hours), and diverse hair types, enabling objective monitoring outside controlled laboratory or inpatient environments. These capabilities directly support ambulatory EEG applications, where long-term monitoring is essential for neurological disease assessment. Such tracking is particularly relevant for neuropsychiatric disorders such as OCD and Tourette's, where objective biomarkers of symptom dynamics are currently lacking (Zrenner et al., 2023), as well as for sleep disorders, where existing diagnostic equipment is costly and ecologically limiting (Arnal et al., 2020). In parallel, the demonstrated MRI compatibility addresses a major barrier to multimodal EEG integration. These findings suggest potential for use in multimodal neuroimaging platforms. Collectively, these results provide converging evidence that dry MXene electrodes represent a promising alternative to gelled EEG for next generation neurodiagnostic and brain monitoring systems.

Disclosures

F.V. is a co-inventor on the US patent. US11925466B2 "Implantable devices using 2D metal carbides and nitrides (MXenes)."

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