Intracranial EEG Phantom for Brain Stimulation Studies

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Background and Project Application

Physiological Background

- Epilepsy is a neurological disorder, characterized by the regular appearance of uncontrollable seizures [1]
  - *Focal epilepsy*: local neuronal network, potential treatment through a temporal lobectomy [1]
- Two brain mapping techniques utilized prior to surgical epilepsy management include intracranial electroencephalography (iEEG) and transcranial magnetic stimulation (TMS) [2]
- There is a lack of clinical explorations in pediatric patients, given added complications surrounding child participation in human studies [3]

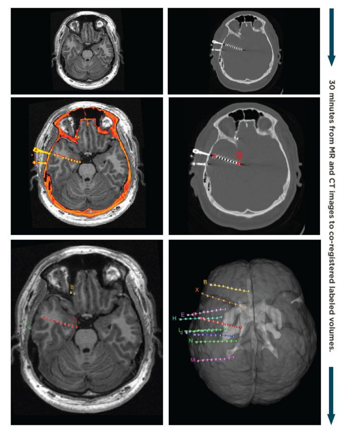

Figure 1. Inserted iEEG electrodes [4].

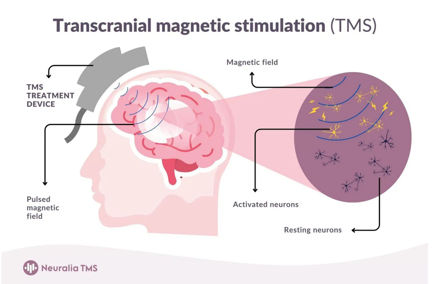

Figure 2. TMS pulse application [5].

Project Applications

- Using both techniques prior to surgery provides the most accurate representation possible
- Constructing a physiologically accurate brain phantom model allows for simulation of TMS treatment while iEEG electrodes are in place
- Special emphasis will be put on representing a pediatric population

Figure 3. Adult iEEG TMS phantom [3].

Problem Statement

The goal of this project is to develop a pediatric brain phantom model that can be used to simulate the following effects of TMS on iEEG electrodes:

- Induced currents
- Changes in temperatures
- Displacement

These observations will determine the relative safety of using these brain mapping techniques in tandem.

Design Specifications

- Represents accurate physiology of average 5-7 year pediatric brain and skull
  - Skull circumference: 50-54 cm [6]
  - Overall brain matter volume: 1,300 cm^3 [7]
- Brain material must have similar electrical conductivity as brain tissue: 0.2-0.5 S/m [8]
- Brain material must have similar thermal properties to brain tissue: 0.536 W/m-K [9]
- After completion of TMS testing, electrodes must have:
  - Charge density: <30 $\mu C/cm^2$ [2]
  - Temperature change: <1 °C [10]
  - Displacement: ~0 mm [11]
- Must comply with MTR Standards 2.4 and 3.3, CFR Standards 882.5802, and ASTM F2182 [12] [13] [14]
- $500 budget

Prototyping and Final Model

Skull

- CT scan of anonymous 5-7 year old patient processed in 3D Slicer
- Model refined in Autodesk Meshmixer and split into two parts to accommodate brain installation
- Skull printed using Formlabs Clear V5 resin

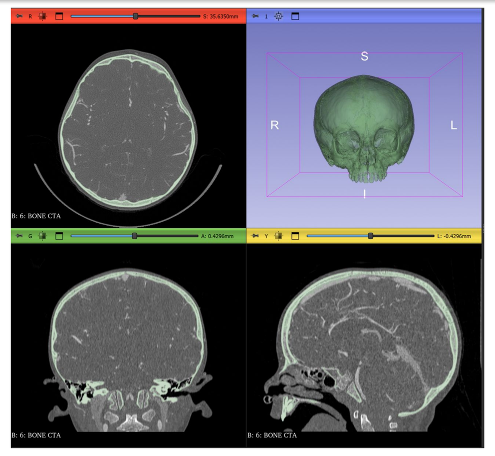

Figure 4. Segmenting pediatric skull model from patient CT scan in 3D Slicer.

Brain Mold

- MRI scan processed in SimNIBS into 3D model
- Brain model 3D printed in ABS and vapor-smoothed using acetone
- Mold created using 15A shore hardness silicone

Hydrogel Brain

- 6% Gelatin Type A [15], 1.2% NaCl
- Solution heated to 65 ℃, cooled to 4 ℃
- Composition validated with thermal and electrical conductivity testing

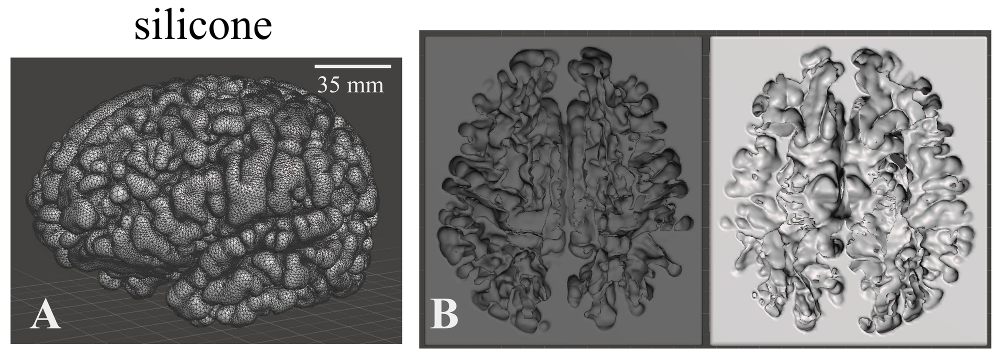

Figure 5. 3D model of brain from processed MRI scan (A) and negative mold created (B).

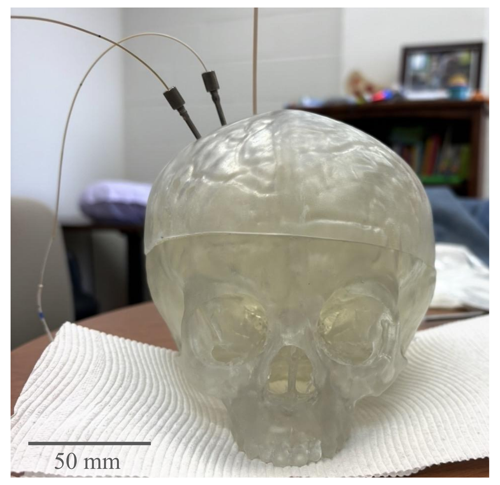

Figure 6. Final model with 6-, 8-, and 10-point depth electrodes inserted into gelatin brain encased in 3D printed resin skull.

Testing

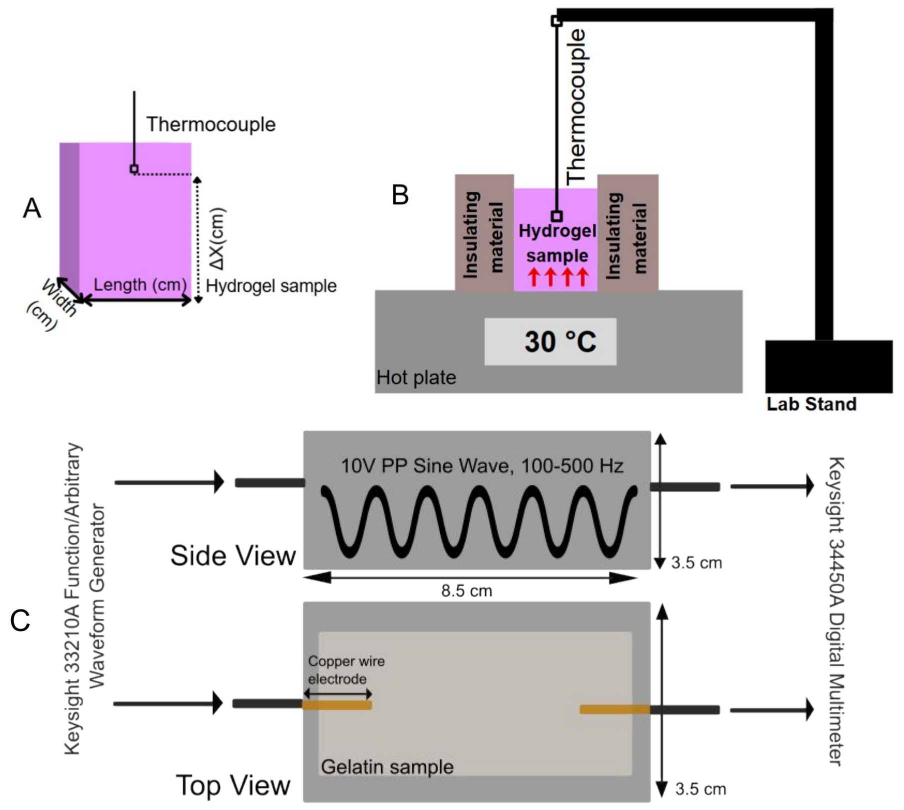

Figure 7. Thermal (A/B) and electrical (C) conductivity testing setups.

Thermal Conductivity Testing

- Wrap hydrogel sample in insulating material
- Place sample on hotplate set to 35 °C
- Insert thermocouple to take temperature measurements periodically
- Choose material and concentration with thermal conductivity closest to 0.536 W/m-K [9]

Electrical Conductivity Testing

- 35mm × 30mm × 85mm gelatin samples
- 2 copper electrodes
- Find voltage and current with varied frequency
  - Keysight 33210A Waveform Generator
  - Keysight 34450A Digital Multimeter
  - Astro AI M4KOR Digital Multimeter
- Saline and hydrogel conc. 0.2-0.5 S/m

Combined iEEG and TMS Testing

- Heating
  - AIOMEST AI-A002 Digital Multimeter
  - 2 thermocouple probes
- Displacement
  - iPhone 16 Pro Camera, 4K 120FPS
  - Analyzed anteriorly and laterally
  - Exposed electrode length before and after
- Induced Current
  - SparkFun VC830L Digital Multimeter
  - Measure from 8 and 10 point electrodes
- Electrode hardware removed for trial 2

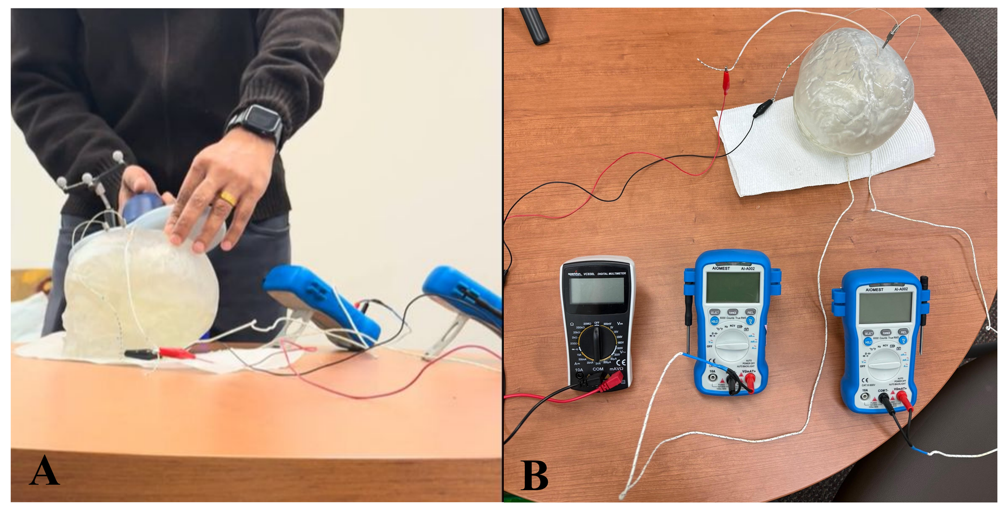

Figure 8. Functional model testing with TMS pulses applied (A) and electrical/thermal data collection (B).

Results

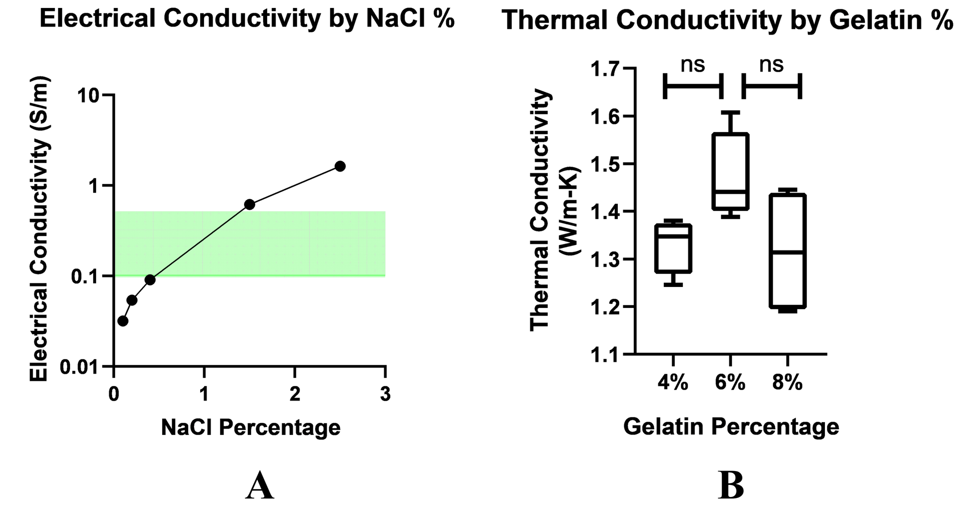

Figure 9. Material testing results for electrical (A) and thermal (B) conductivity based on saline and gelatin percentage.

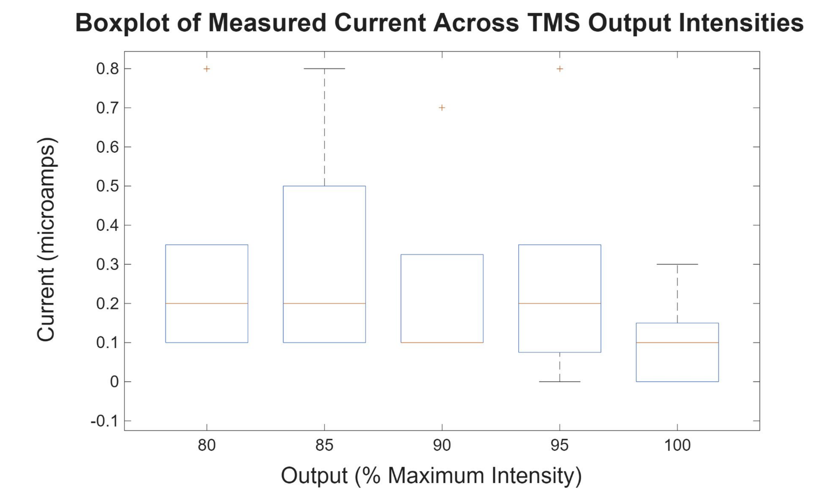

Figure 10. Induced current measurement upon TMS pulse application to final prototype.

Combined iEEG and TMS Results

- Heating
  - Trial 1: ≤ 1 ℃
  - Trial 2: ≤ 1 ℃
- Displacement
  - Trial 1: 0.65 ± 0.64 mm
  - Trial 2: 0.57 ± 0.90 mm
- Induced Current
  - Trial 1: 0 ± 0 μA
  - Trial 2: 0.24 ± 0.08 μA

Discussion and Future Work

Discussion

- Electrical properties are tunable via NaCl doping
- Thermal conductivity not significantly affected by gelatin % or NaCl
- Need improved sensitivity on prototype testing equipment
  - Temperature measurements at 1 °C sensitivity
  - Improve video recording resolution

Future Work

- Iterate on prototype fabrication; improve gel molding process
- Rheological testing of gel mechanical properties
- Add complexity to model and testing
  - Non-uniform material properties
  - Model in-clinic patient testing setup
- Improve equipment quality for temperature, displacement, and current measurements

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