



Individualized Head Modeling and Electric Field Simulation in tDCS, ECT, and TMS

Current and Emerging Approaches

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National Institute of Mental Health, NIH

Disclosures

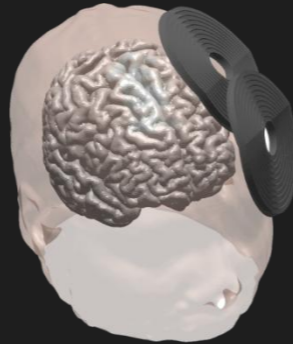
- I am inventor on patents and patent applications on brain stimulation technologies, own by NIH, MIT, Columbia University, University of New Mexico, and NEVA Electromagnetics.

Transcranial brain stimulation: Magnetic vs electric

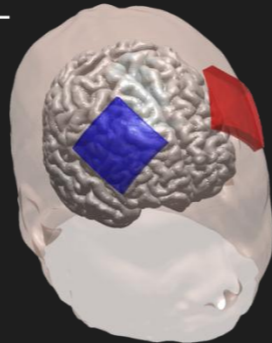
Magnetic (TMS, MST, LFMS, etc.)



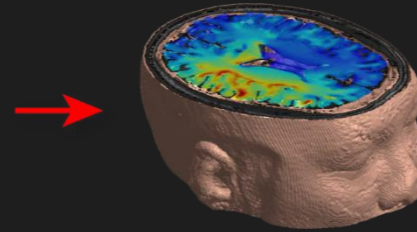
Coil



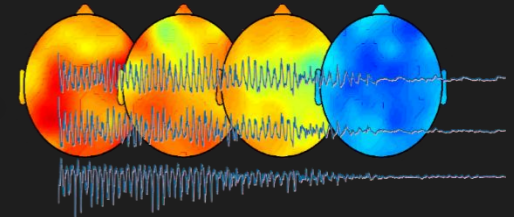
Electric (ECT, tDCS, tACS, etc.)



Electrodes



Electric field



Change in neural activity

Quasistatic approximation

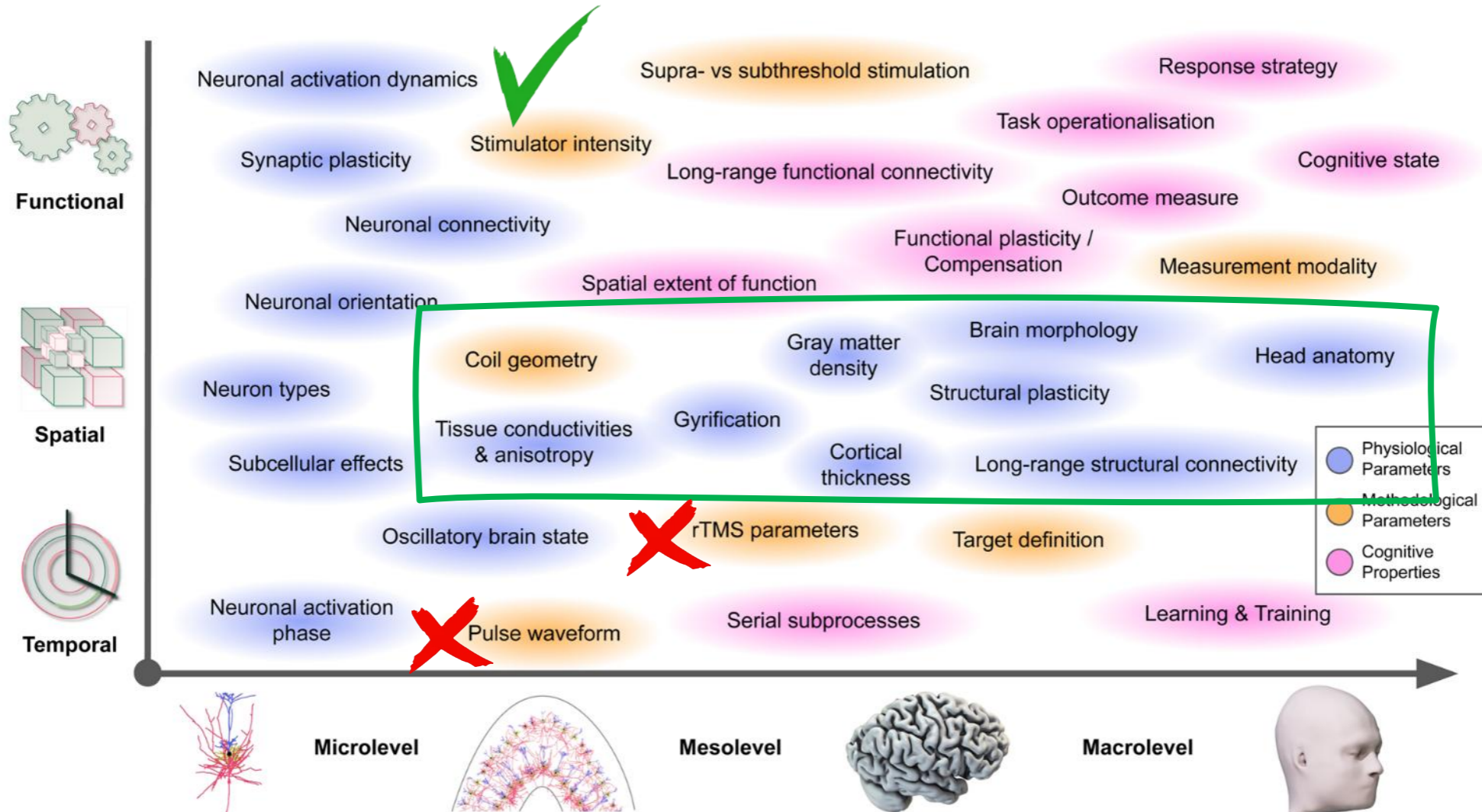
Core assumption

- Frequency is low (≤ 10 kHz), such that $\omega\epsilon \ll \sigma$, that is, displacement currents negligible; tissue behaves purely resistive

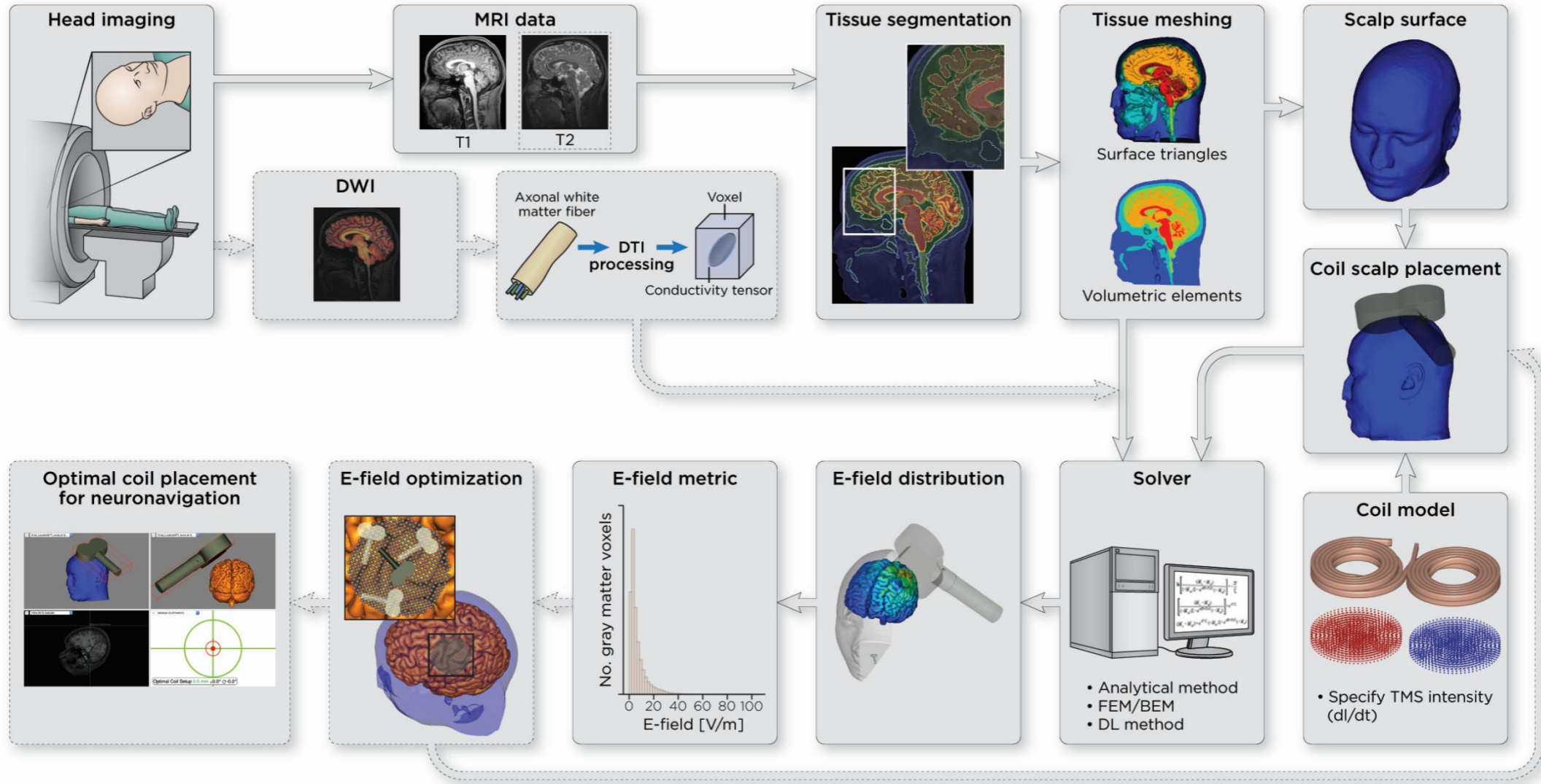
Practical implication

- E-field $\mathbf{E}(\mathbf{r}, t) = \mathbf{E}_0(\mathbf{r}) \cdot w(t)$ solution can be factored into a temporal waveform $w(t)$ and a static spatial distribution $\mathbf{E}_0(\mathbf{r})$
- The waveform modulates the amplitude of the whole spatial map up and down uniformly

Dose components captured by E-field models



Modeling pipeline



Electrical conductivities

- ↯ Common electrical conductivity values used in tES and TMS modeling
- ↯ **Vaveats:** historically, measurements of tissue conductivity has been sparse, individual variation not accounted for, as is tissue heterogeneity, frequency dependence, nonlinear effects, age effects, hormonal effects, etc.
- ↯ Nevertheless, using these approximately correct values has been shown to have been useful for model comparisons

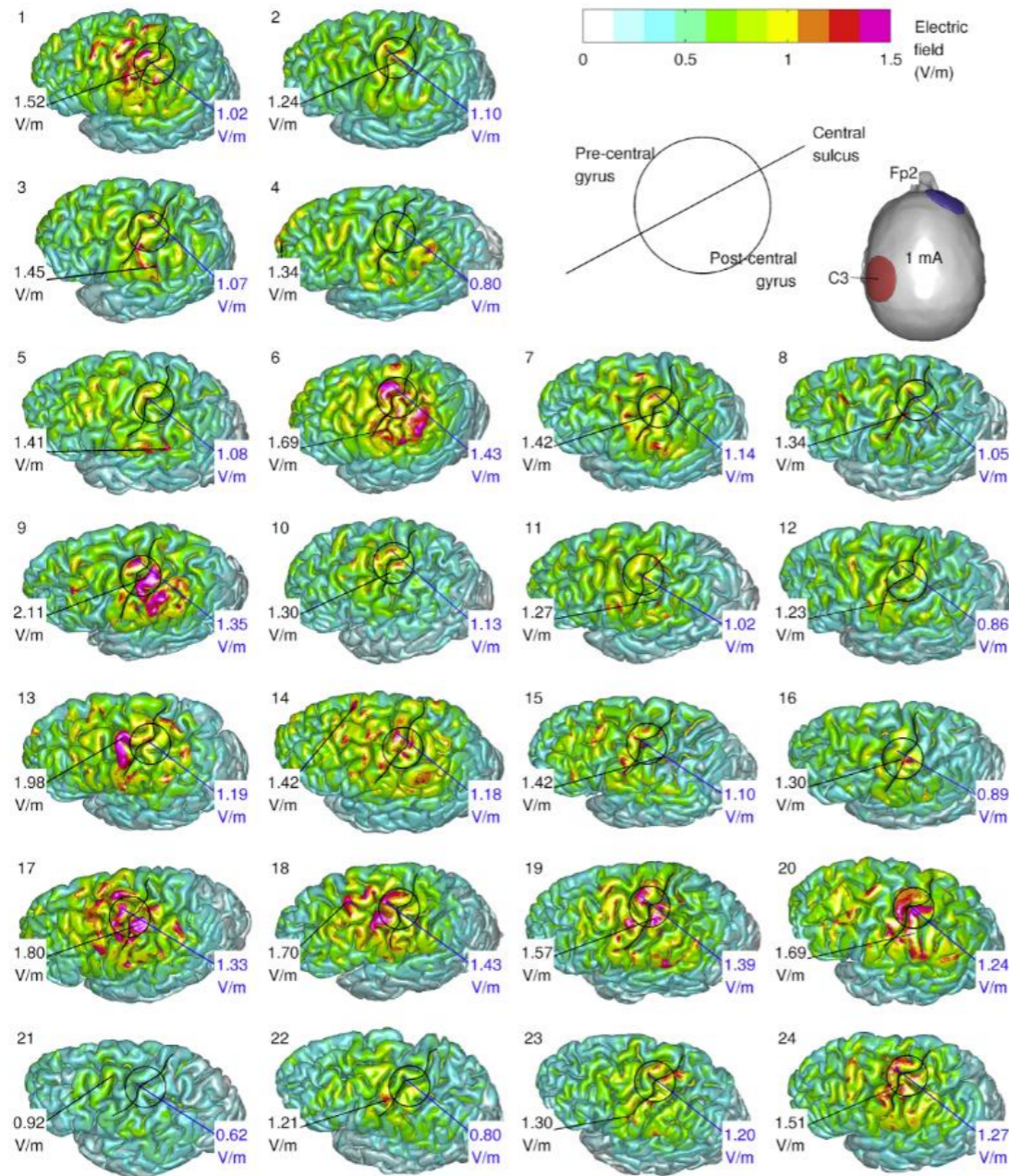
Tissue/material	Conductivity (S/m)
Scalp/skin	0.465
Skull	0.01
Cerebrospinal fluid	1.65
Gray matter	0.276
White matter	0.126
Fat	0.025
Saline-soaked sponge	1.4
Electrolyte gel	0.3-8
Electrode/coil metal conductor (copper)	5.8×10^7

Inter-subject variability in tDCS

↳ 24 males, age 38.6 +/- 11.2

↳ Individual FEM models of motor tDCS (C3 anode, Fp2 cathode)

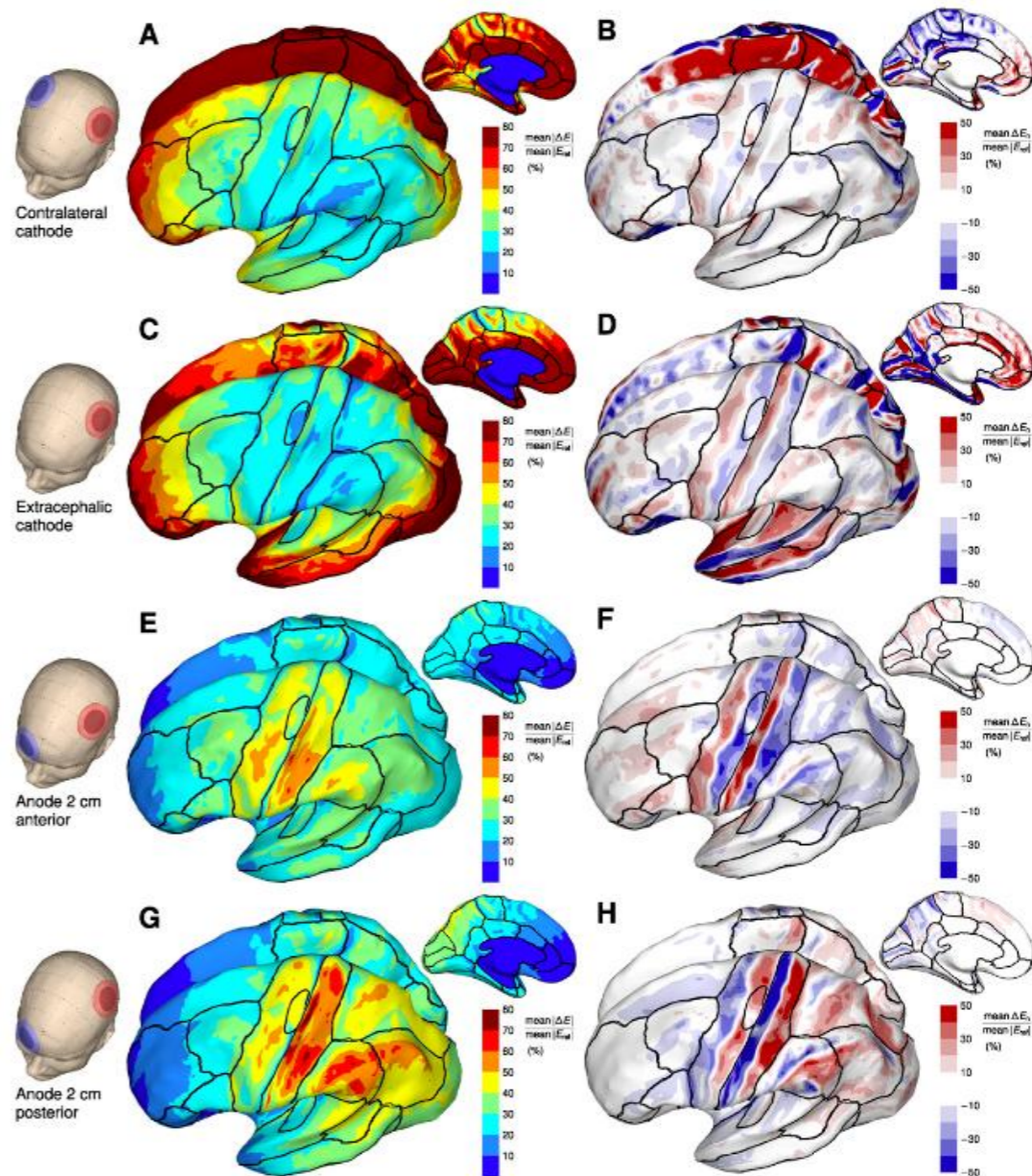
↳ Large differences in each individual's E-field distribution



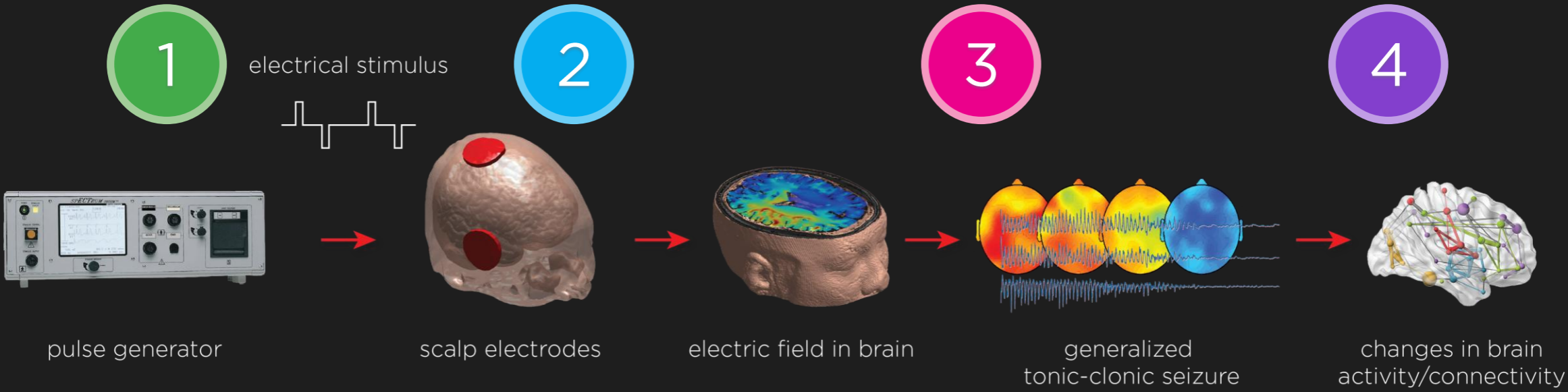
Inter-subject variability in tDCS

- ↳ 62 FEM models
- ↳ 16 electrode montages including motor cortical, frontal, and extracephalic tDCS
- ↳ Group-level E-fields mapped onto a common space
- ↳ “Results reveal the E-fields and their variability at the group level in the standard brain space, providing insights into the mechanisms of tDCS for plasticity induction.”

しばらく
Shibaraku



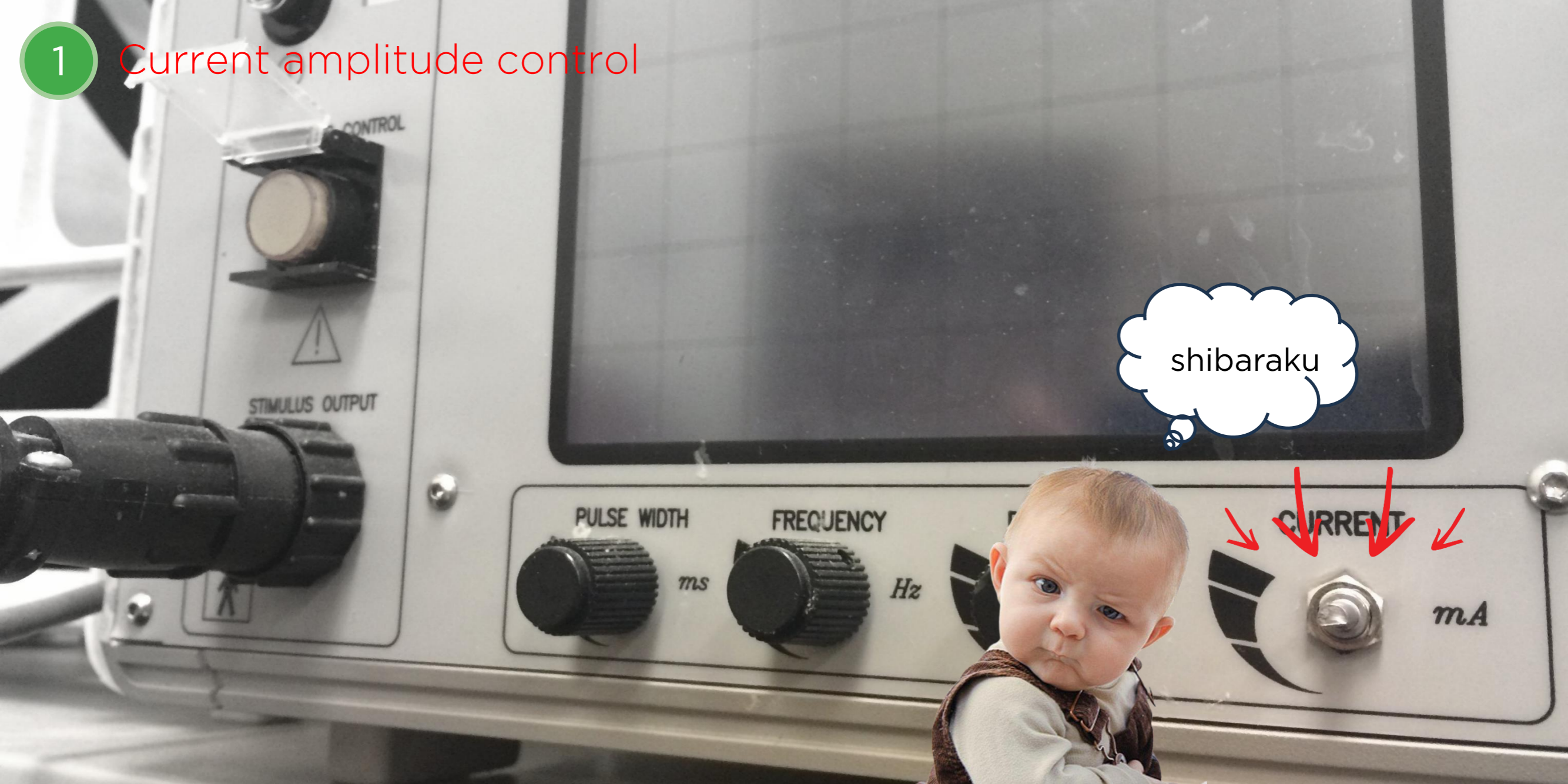
Electroconvulsive therapy (ECT)



1

Current amplitude control

shibaraku



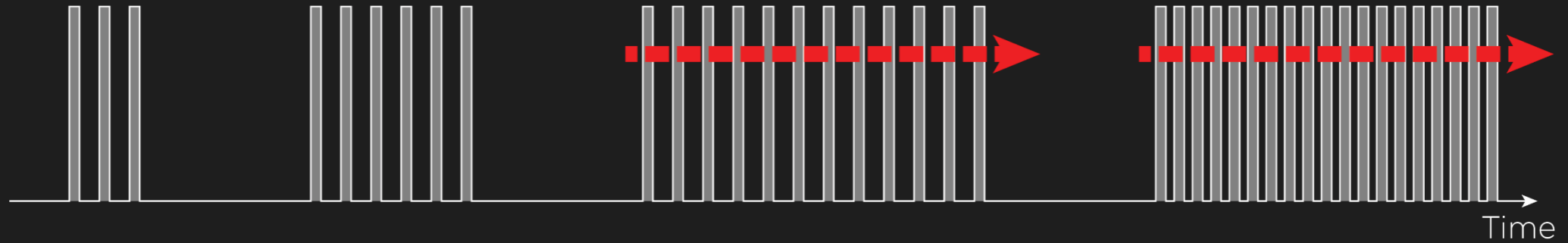
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Conventional ECT titration

fix pulse amplitude @ 800 mA

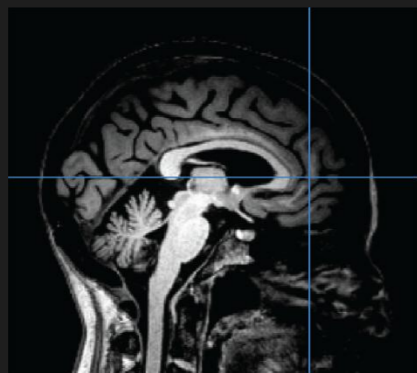
increase pulse train duration

increase pulse train frequency

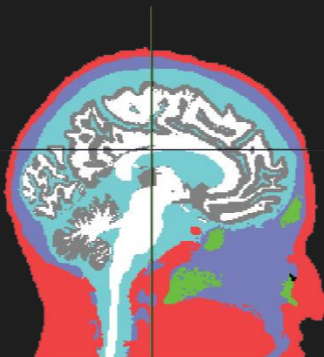


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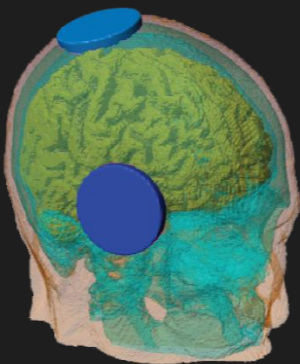
Computational electric field modeling



individual MRI

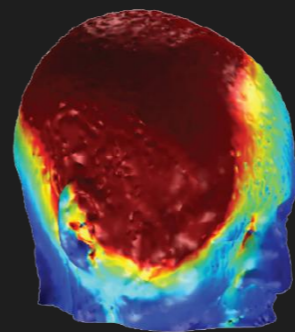


tissue segmentation

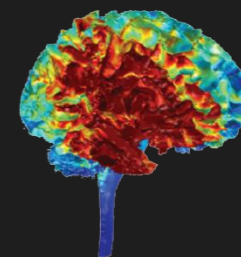


electrode geometry & placement

$$\nabla \cdot \sigma \nabla \phi = 0$$
$$\mathbf{E} = -\nabla \phi$$



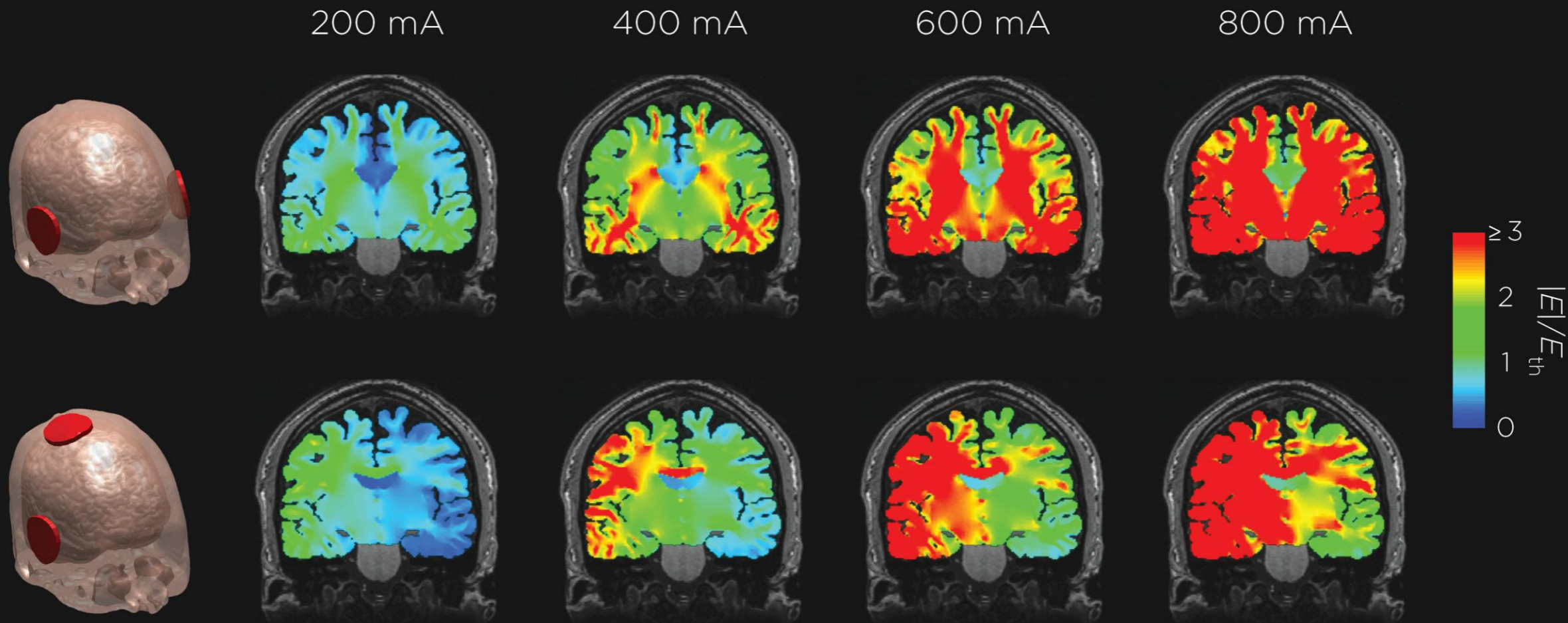
finite element solver



electric field analysis

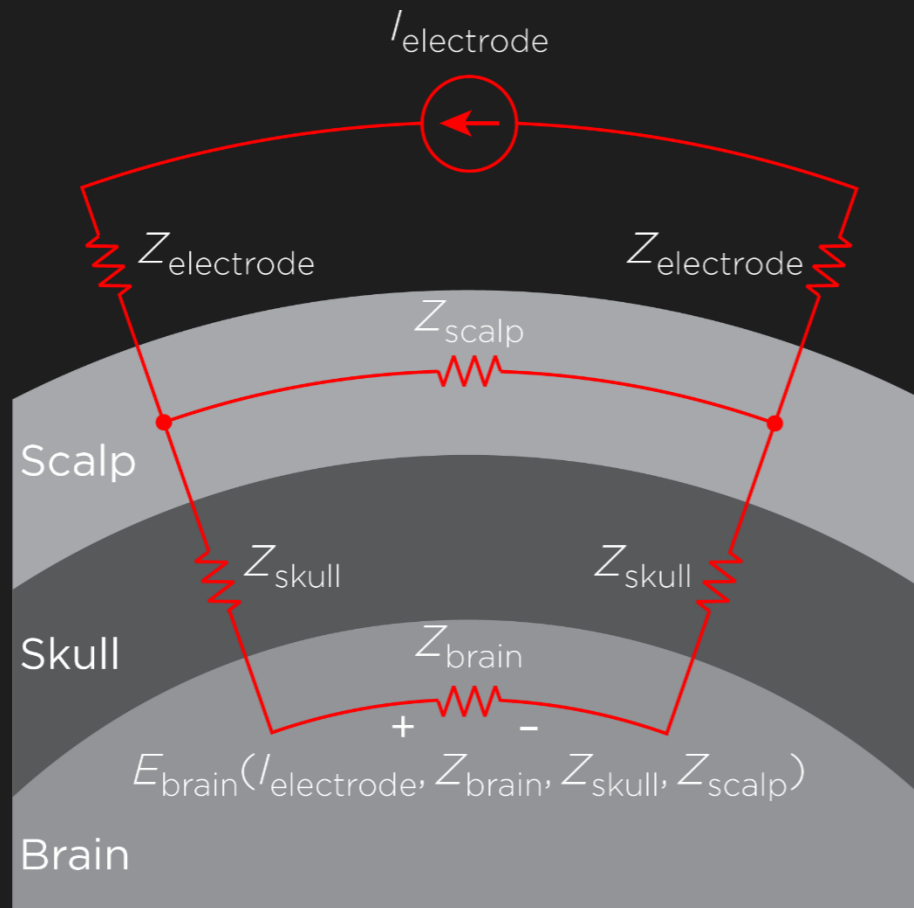
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High current amplitude contributes to **side effects**



1

Fixed current amplitude contributes to **variability**



Fixed electrode current



Variable tissue impedance



Variable intracranial electric field

Physical Properties and Quantification of the ECT Stimulus: I. Basic Principles

*†Harold A. Sackeim, Ph.D., ‡James Long, B.A., *Bruce Luber, Ph.D.,
*†James R. Moeller, Ph.D., §†Isak Prohovnik, Ph.D., *†D. P. Devanand, M.D.,
and *†Mitchell S. Nobler, M.D.

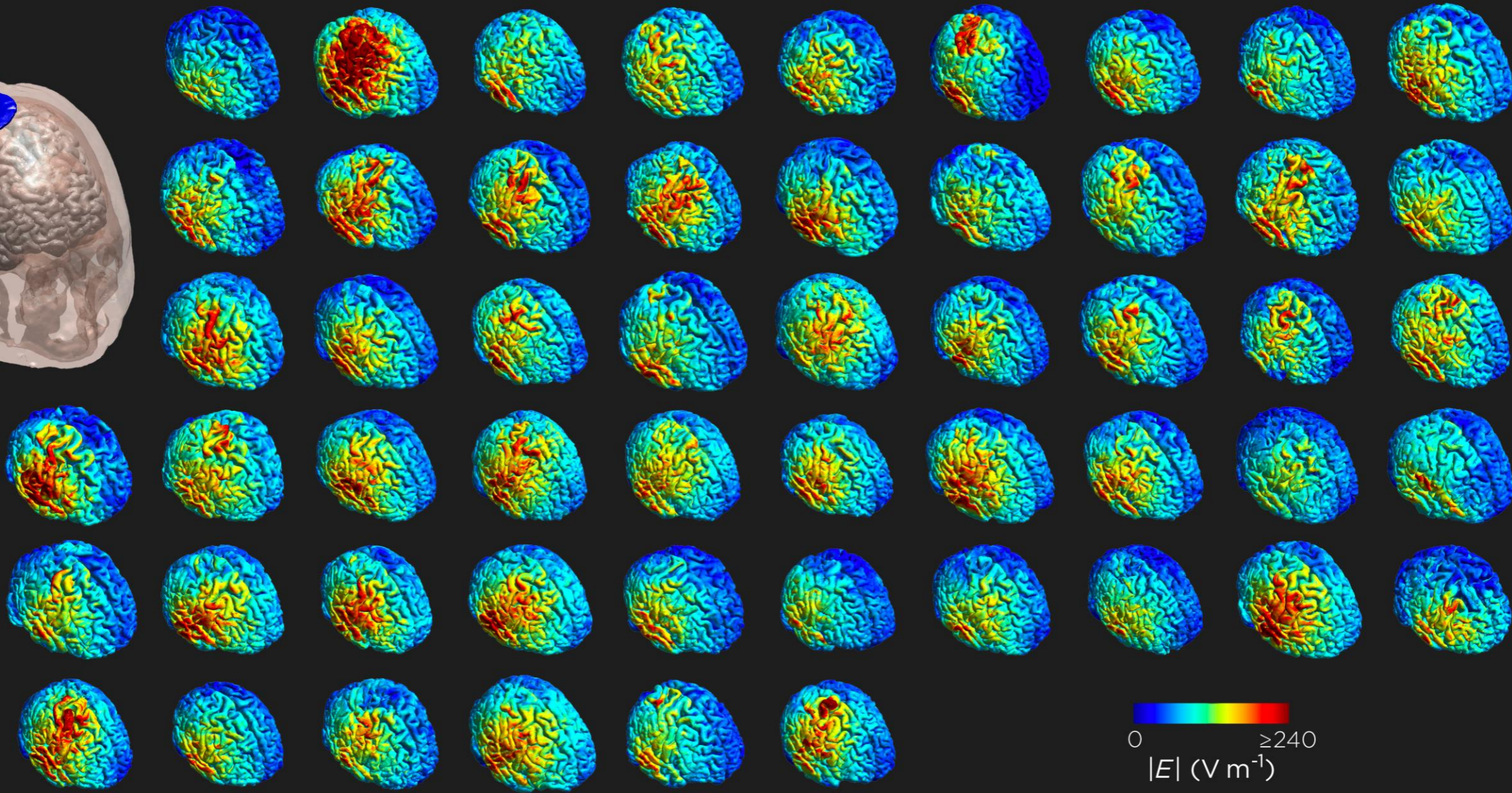
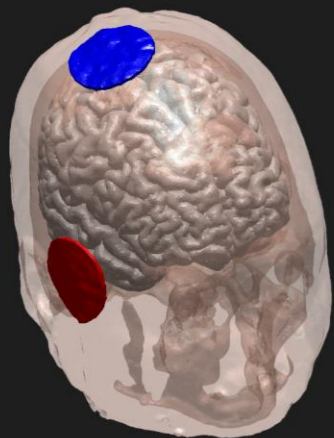
**Departments of Biological Psychiatry and §Brain Imaging, New York State Psychiatric
Institute, New York; †Department of Psychiatry, College of Physicians and Surgeons, Columbia
University, New York; and the ‡James Long Company, Bedford Hills, New York, U.S.A.*

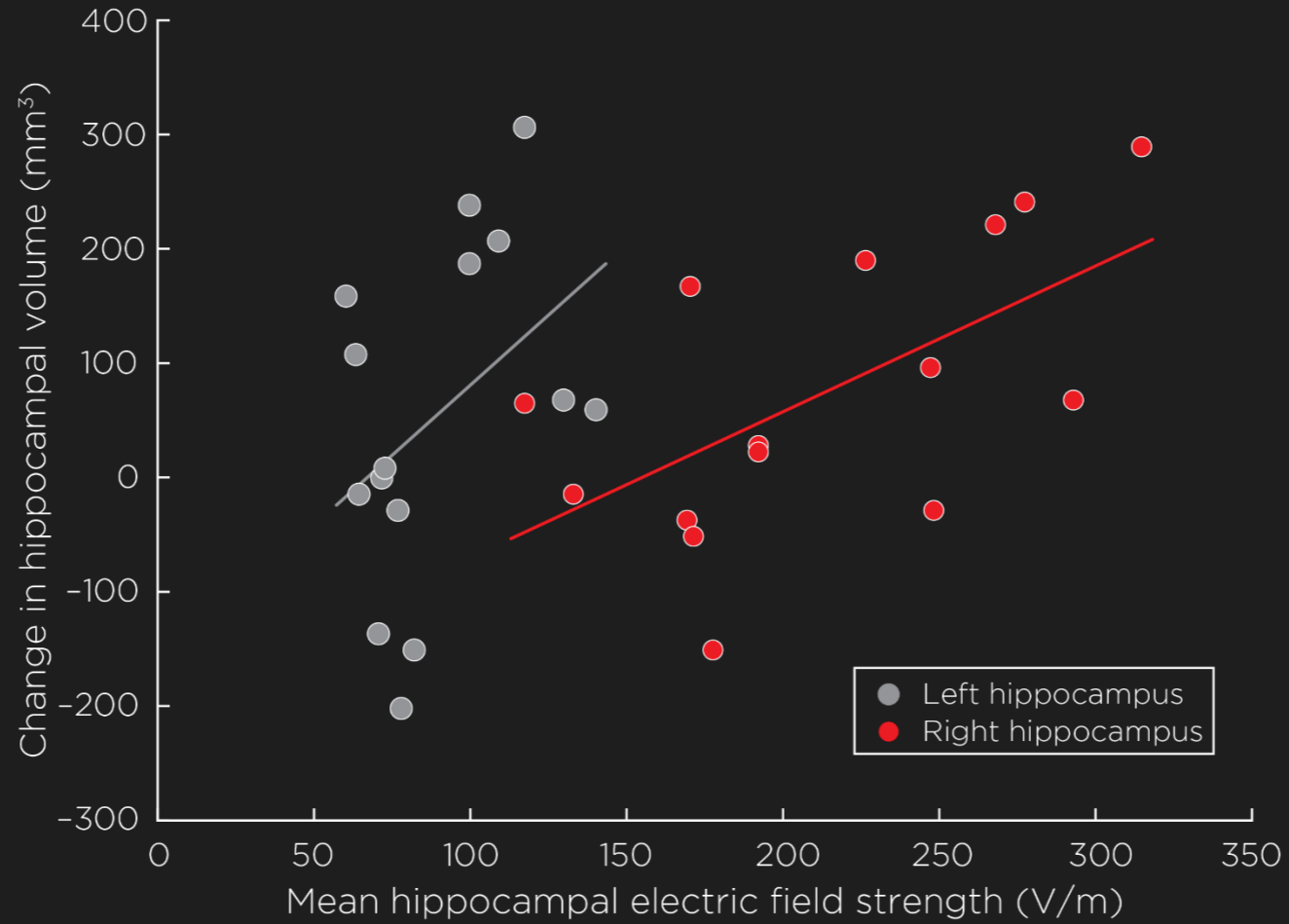
Summary: The physical properties of the electroconvulsive therapy (ECT) stimulus markedly affect both efficacy and side effects. We review basic principles in characterizing these physical properties and in quantifying the ECT stimulus. The topics discussed include the application of Ohm's law, alternative composite units of ECT dosage (energy and charge), the use of constant-current, constant-voltage, and constant-energy principles in ECT devices, the nature of current shunting in ECT and the determinants of impedance, the relations between impedance and seizure threshold, the seizure-eliciting efficiency of alternative stimulus waveforms and of stimulus parameter configurations, and the role of reactive components (capacitance and inductance) in the ECT circuit. New findings are also presented regarding several of these issues.

“

For constant-current stimulation, we suggest that, in general clinical practice, the range of the threshold for seizure elicitation may be as wide as **40-fold**.

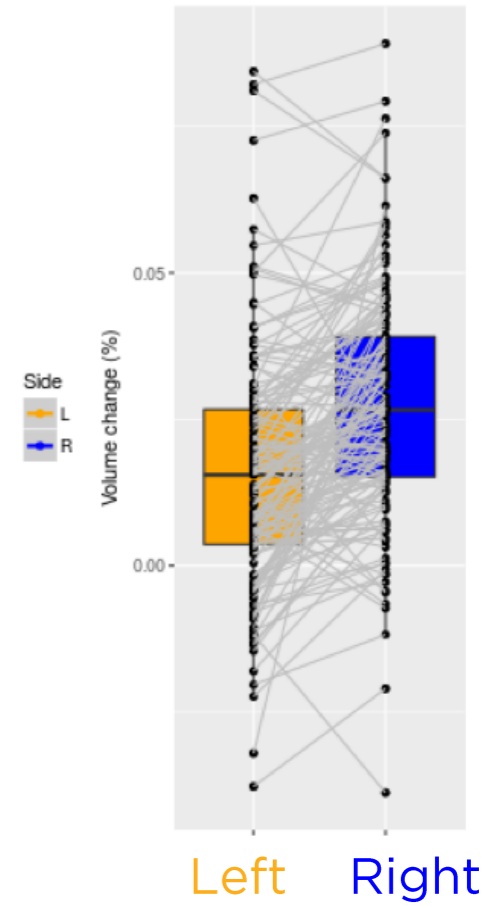
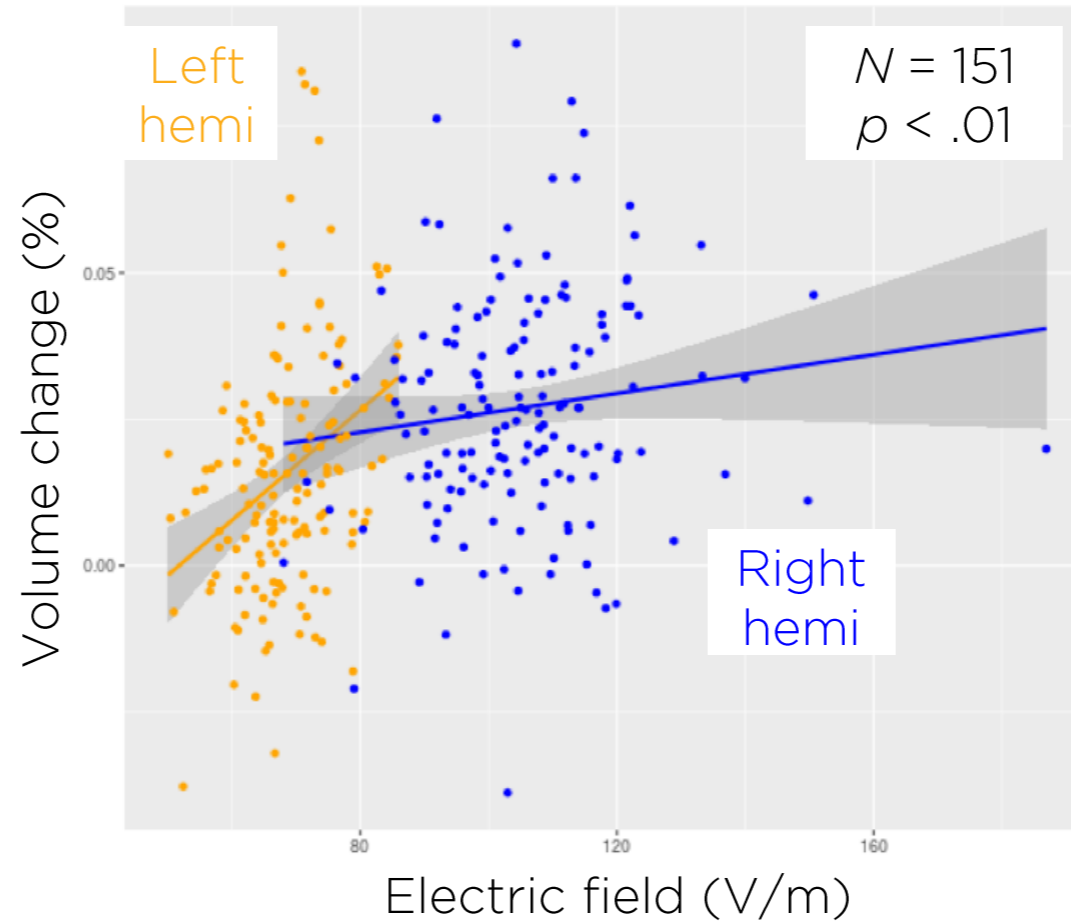
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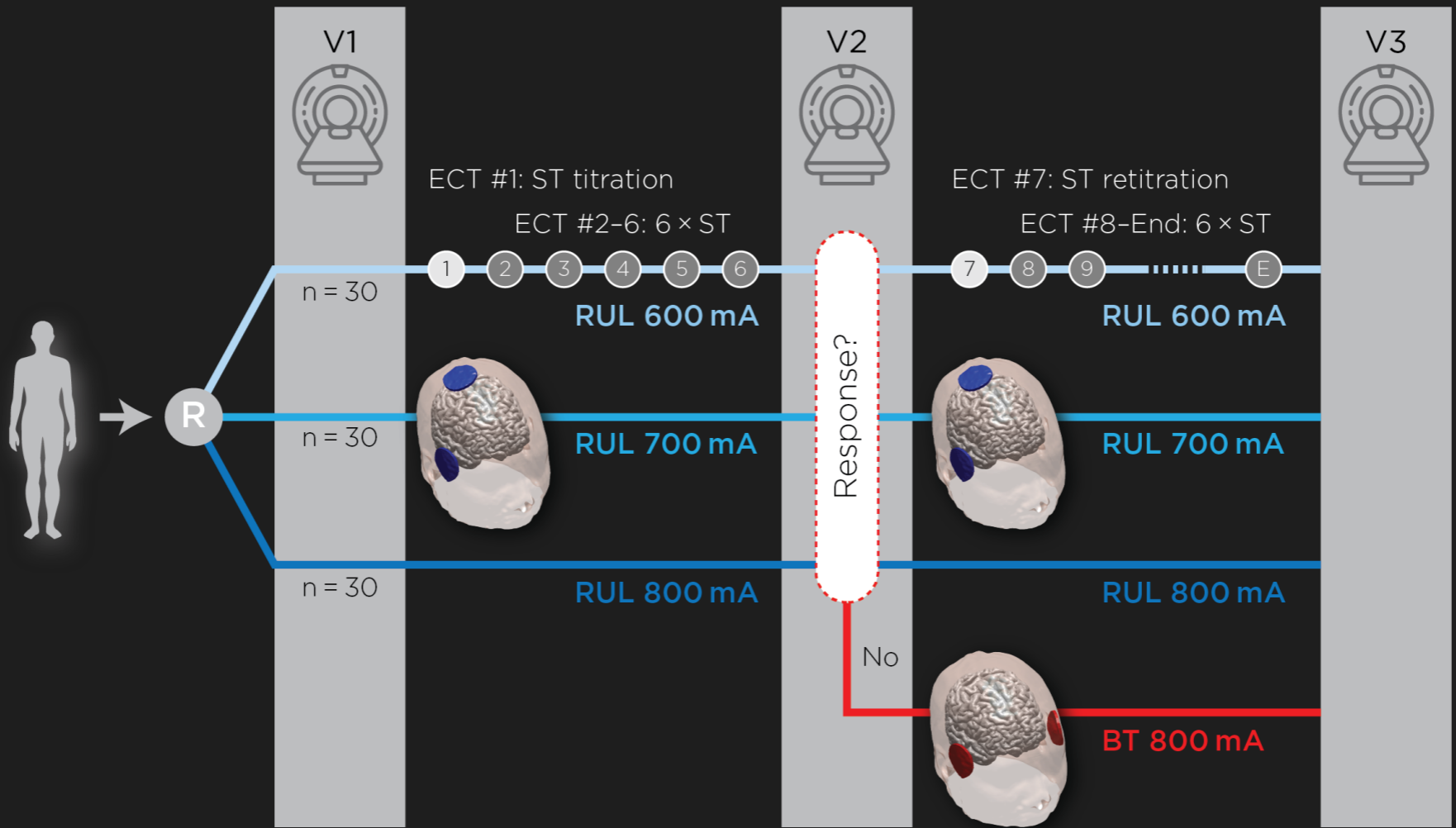


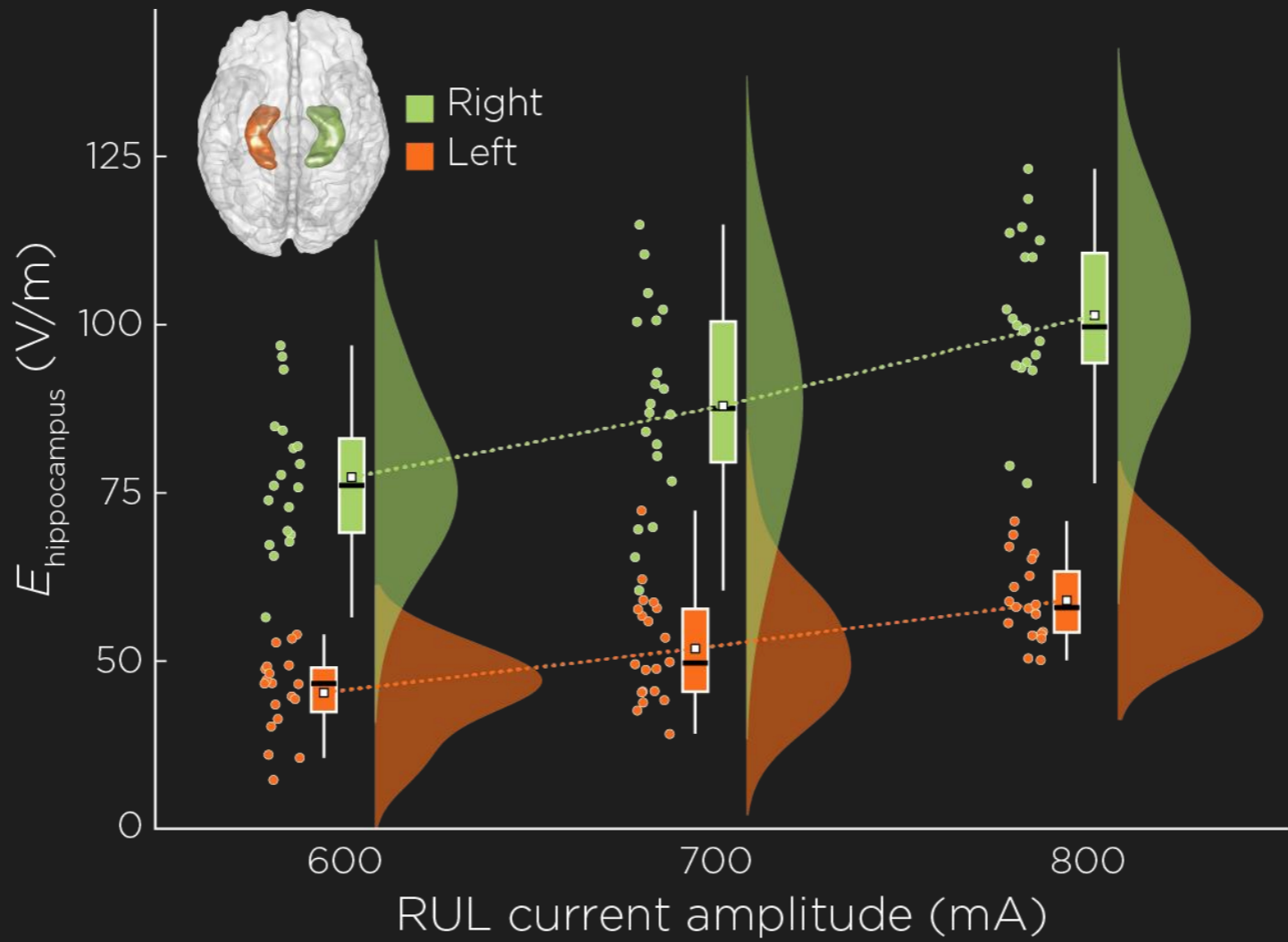


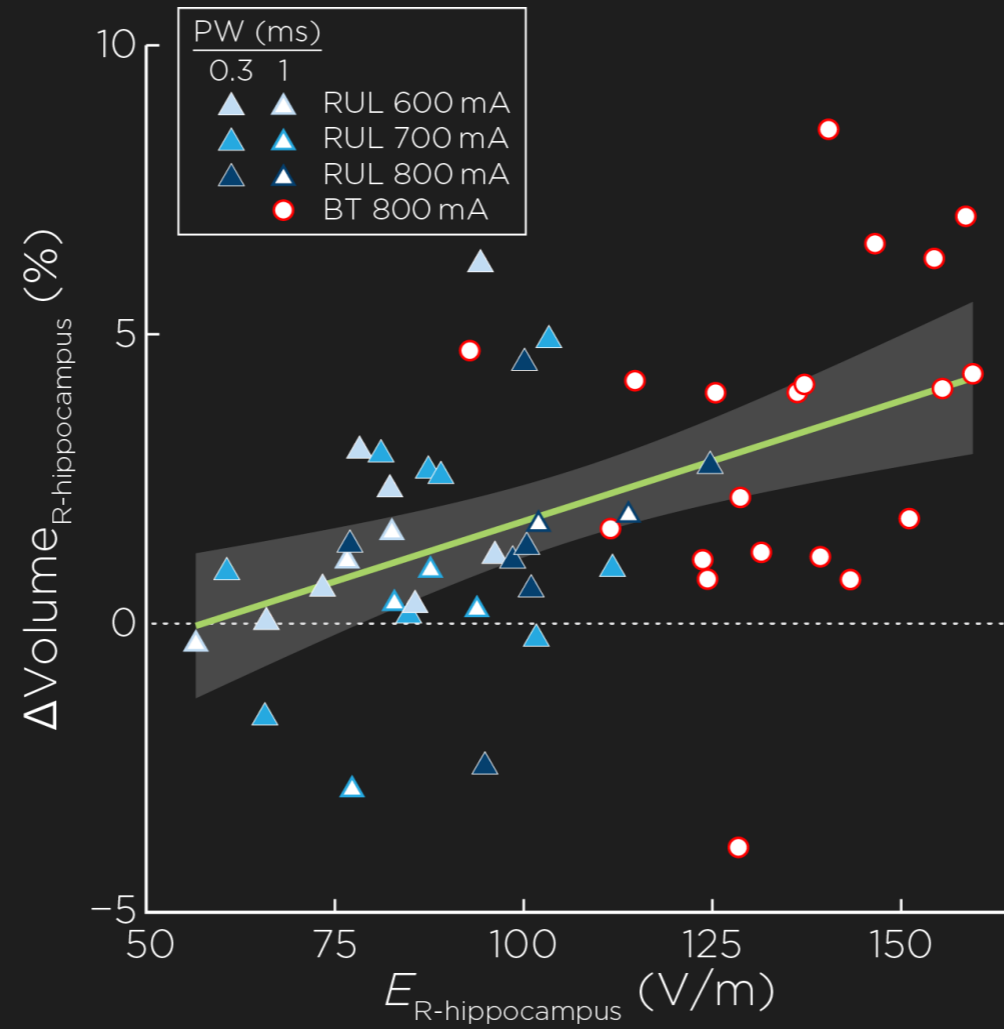
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Global ECT-MRI Research Collaboration (GEMRIC)

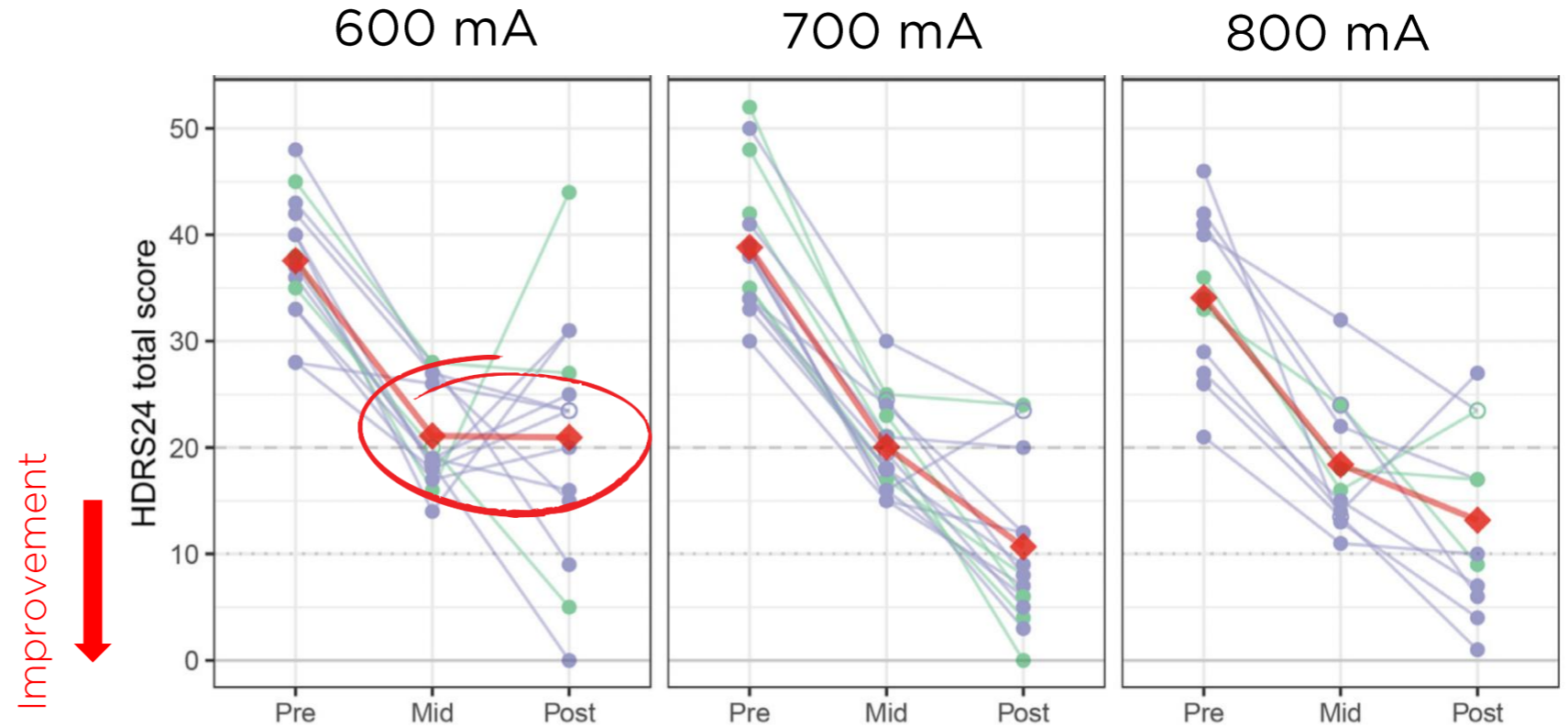






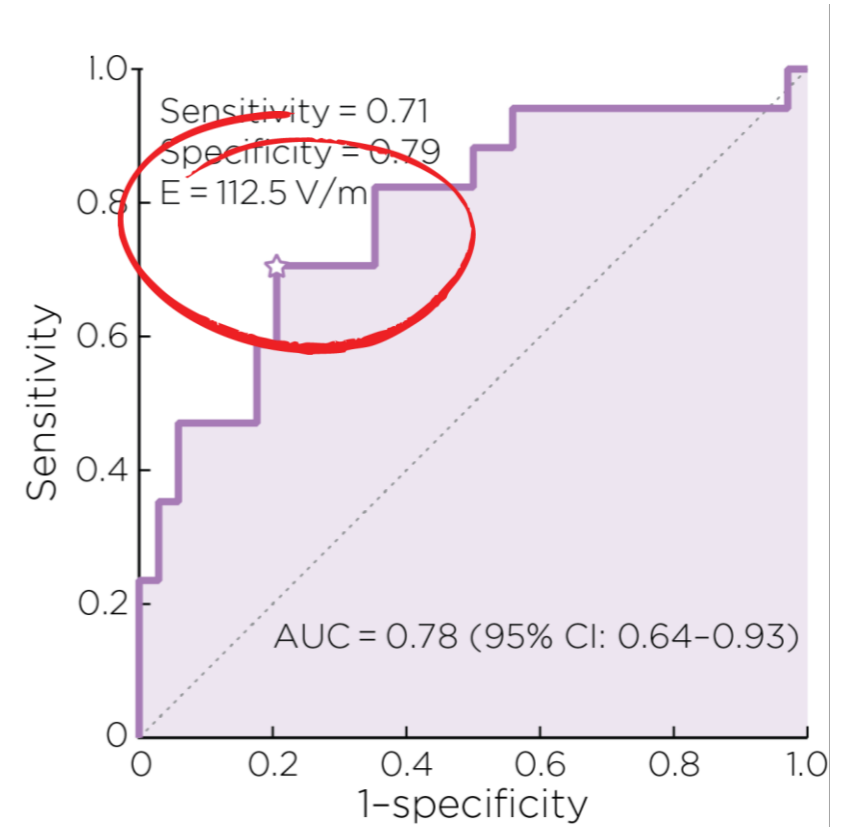
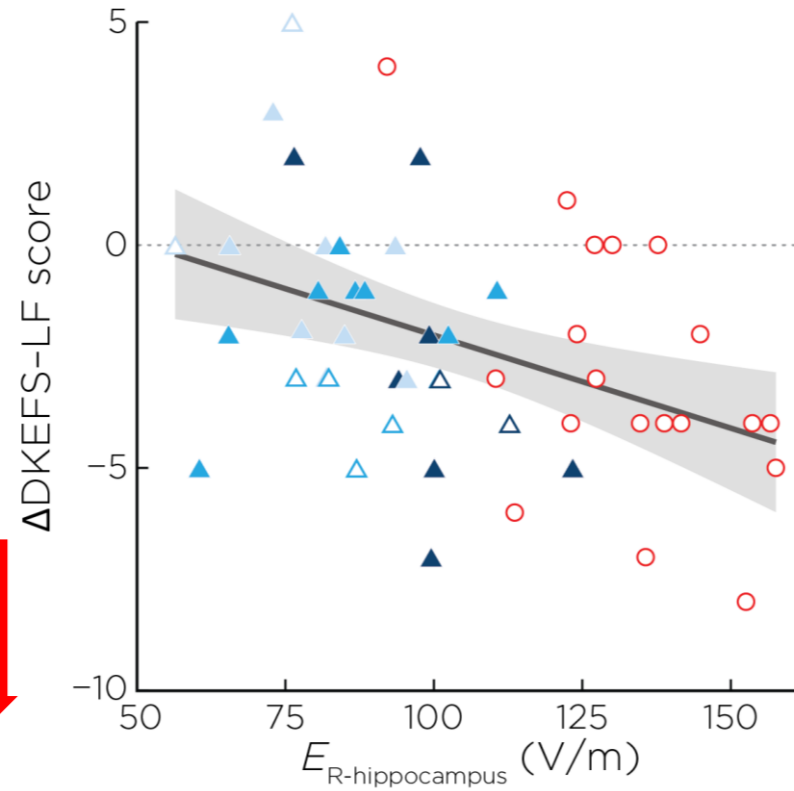


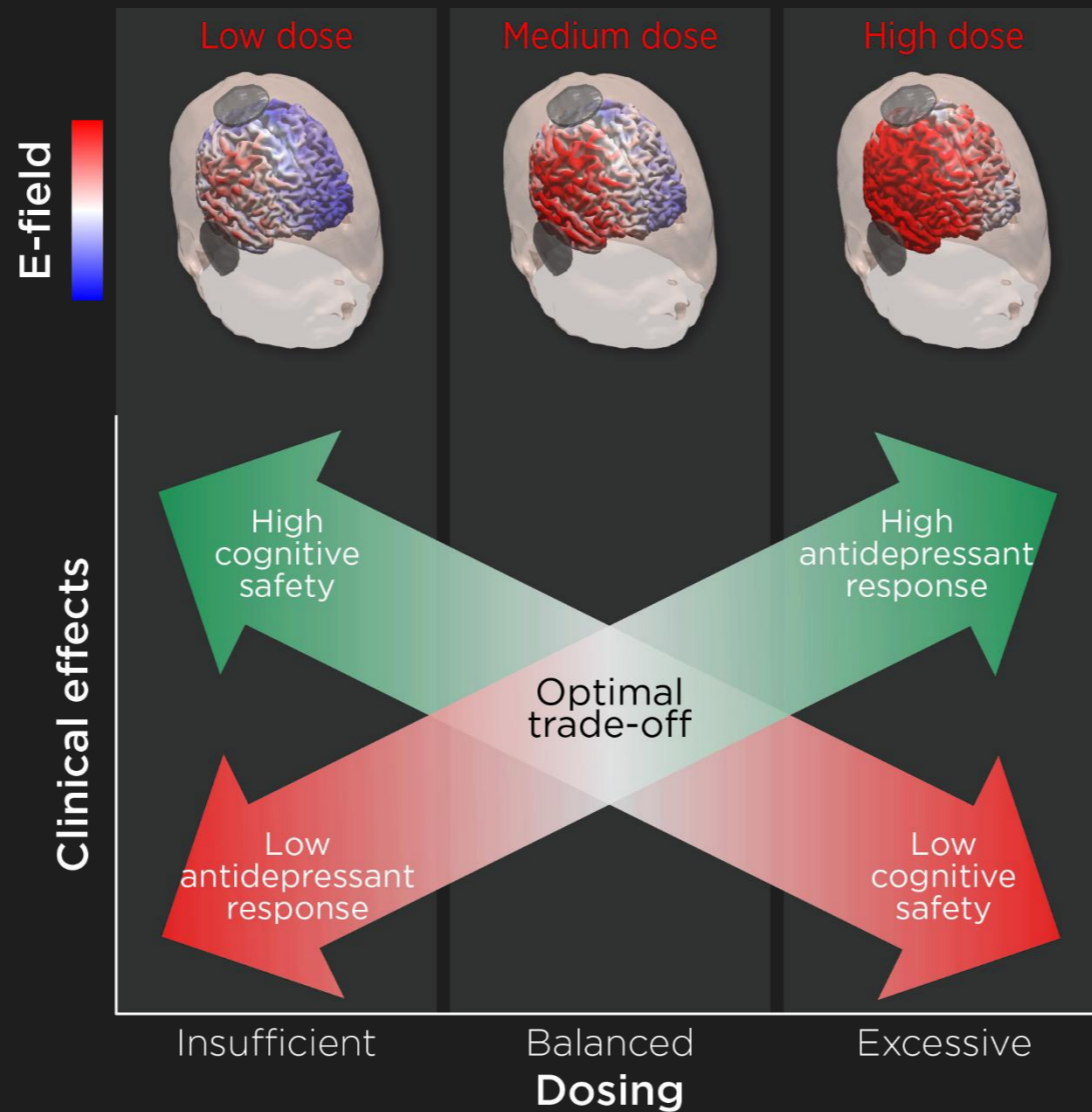
Lower amplitude
comprises efficacy



Higher amplitude associated with cognitive impairment

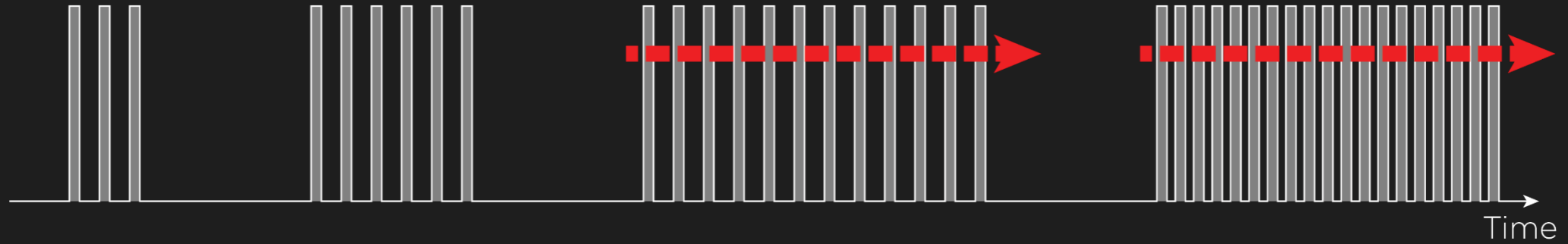
Cognitive impairment



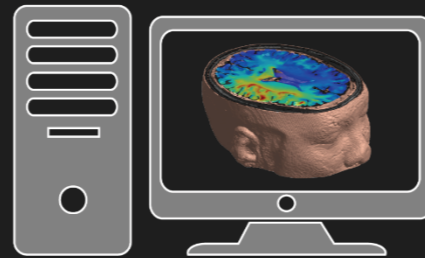
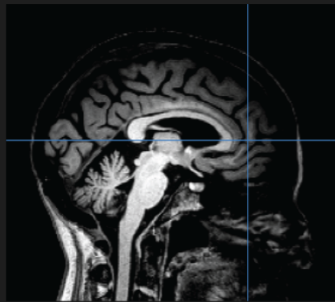


Conventional ECT titration

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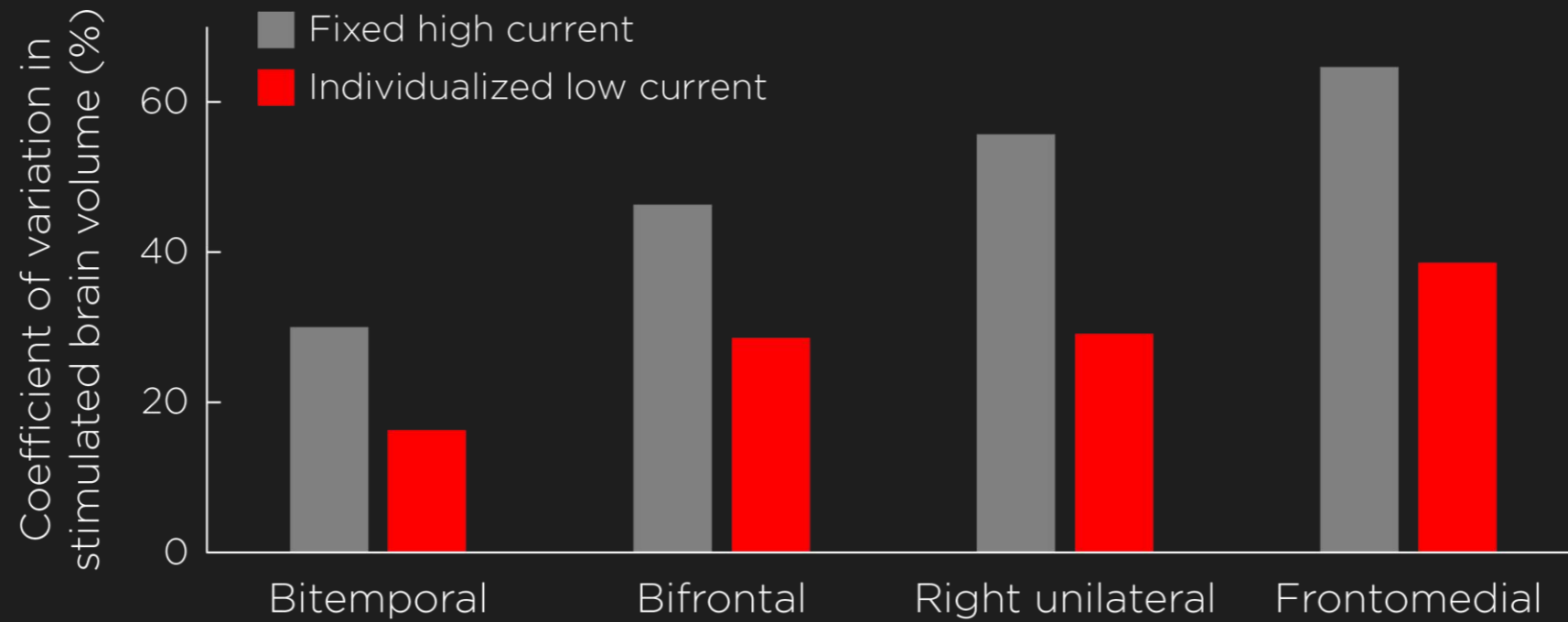
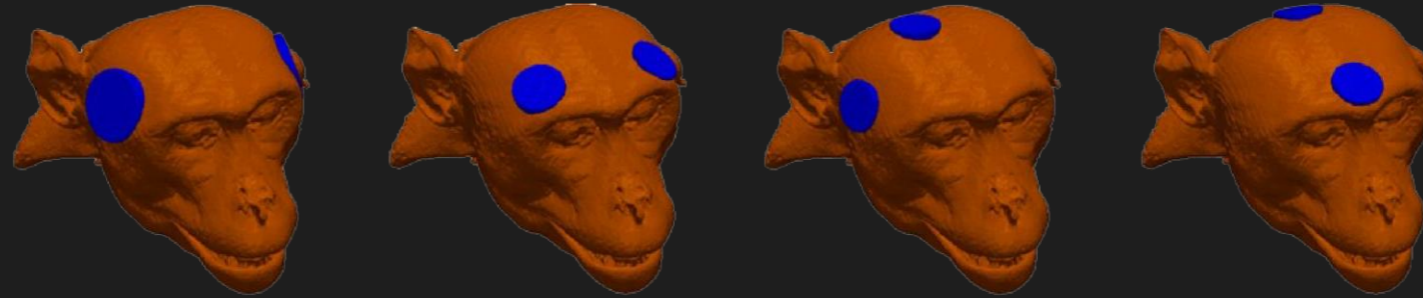


E-field informed ECT



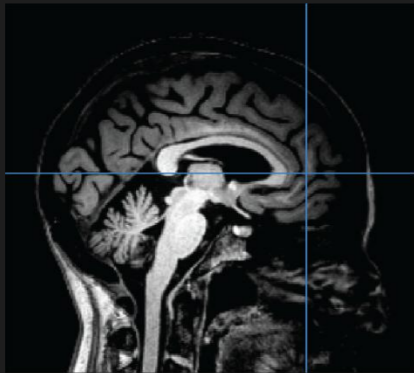
individualized current amplitude
below the cognitive safety threshold



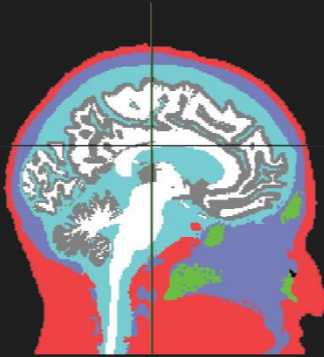


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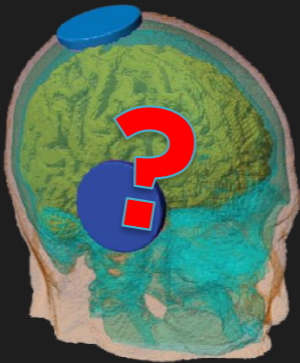
Run this backwards...



individual MRI

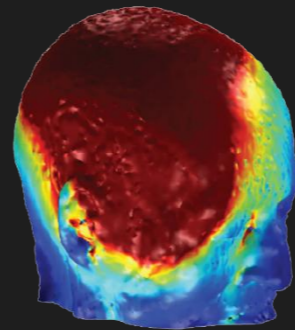


tissue segmentation

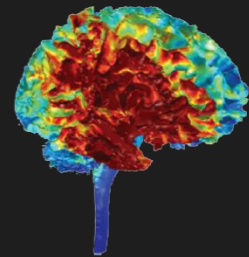


electrode geometry
& placement

$$\nabla \cdot \sigma \nabla \phi = 0$$
$$\mathbf{E} = -\nabla \phi$$

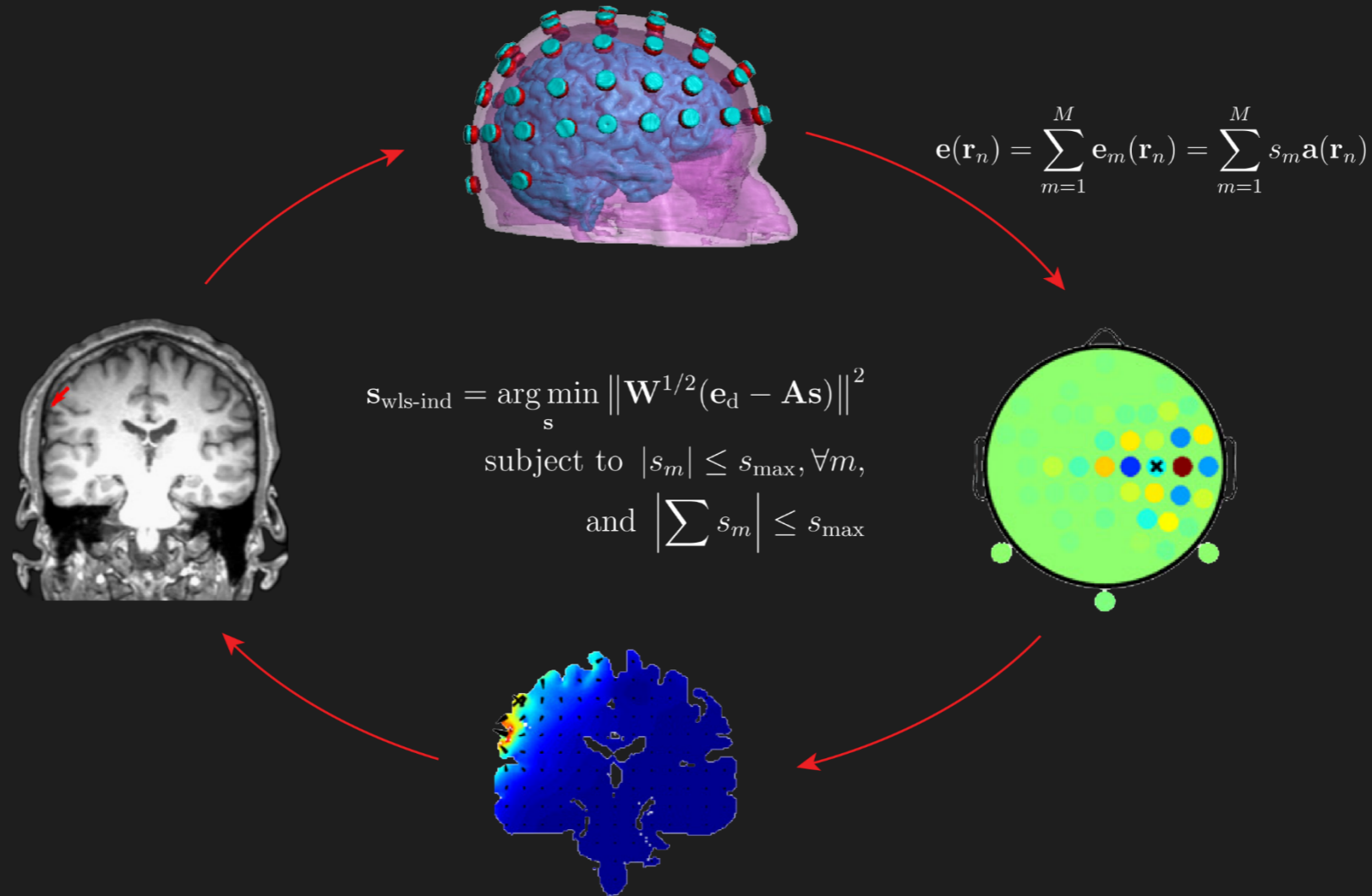


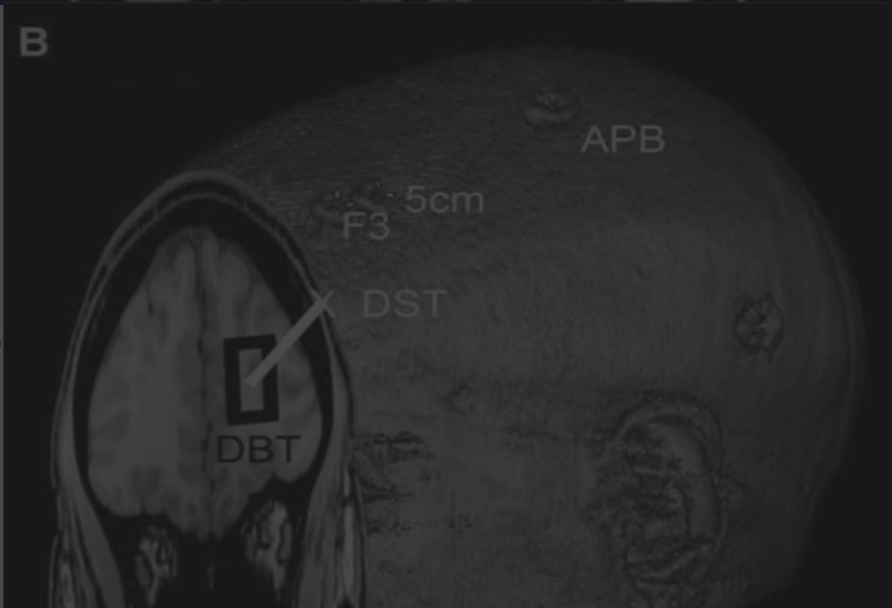
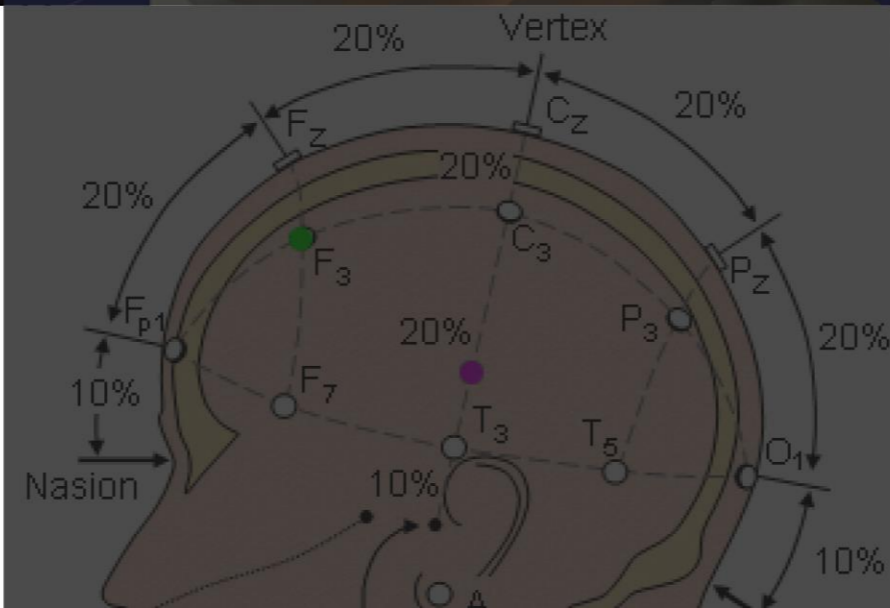
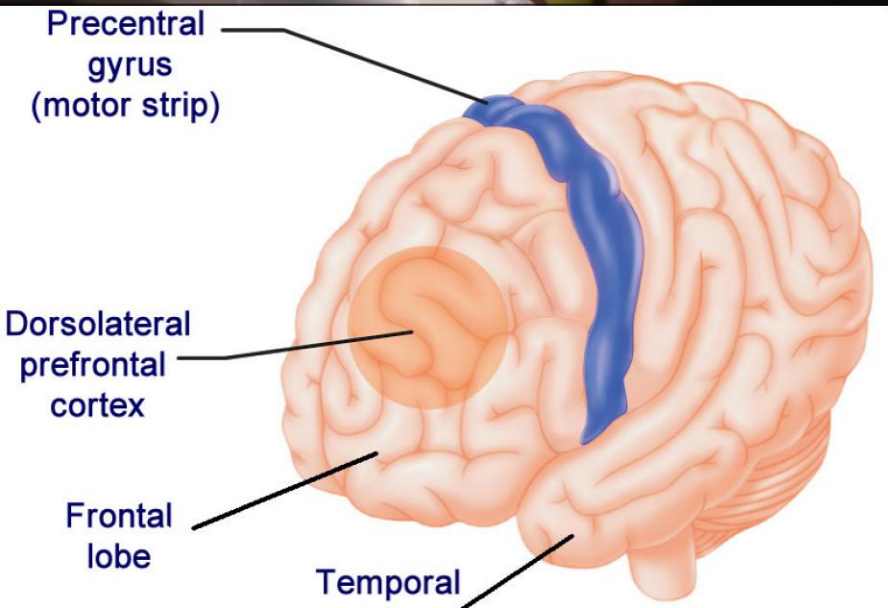
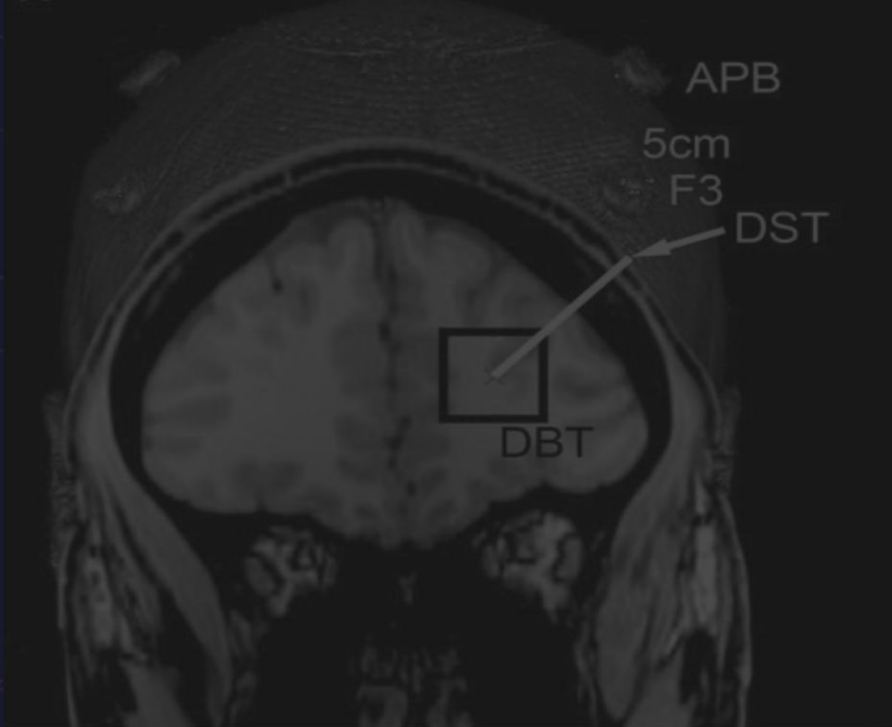
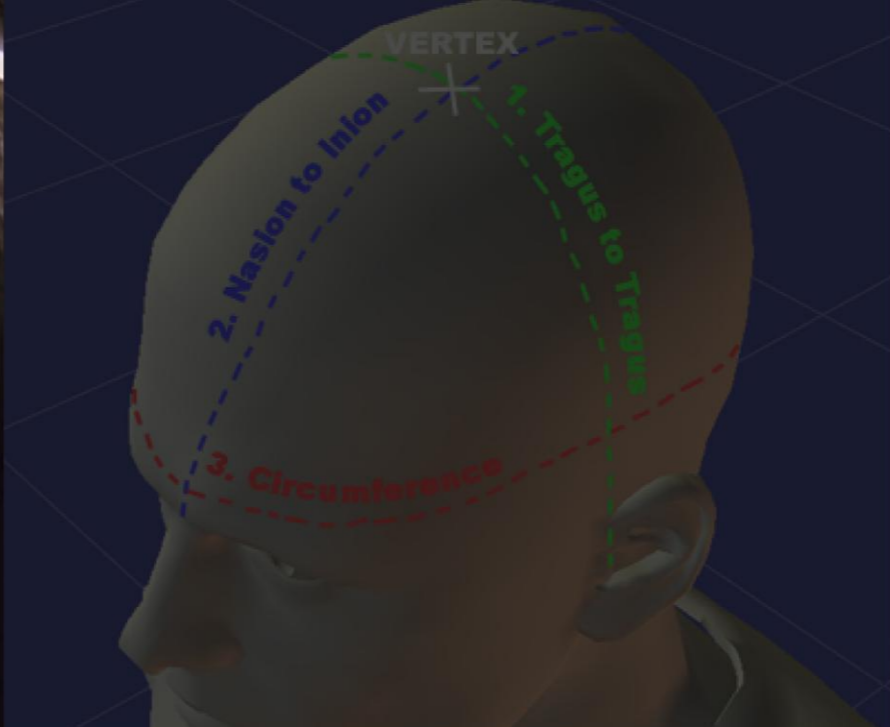
finite element solver

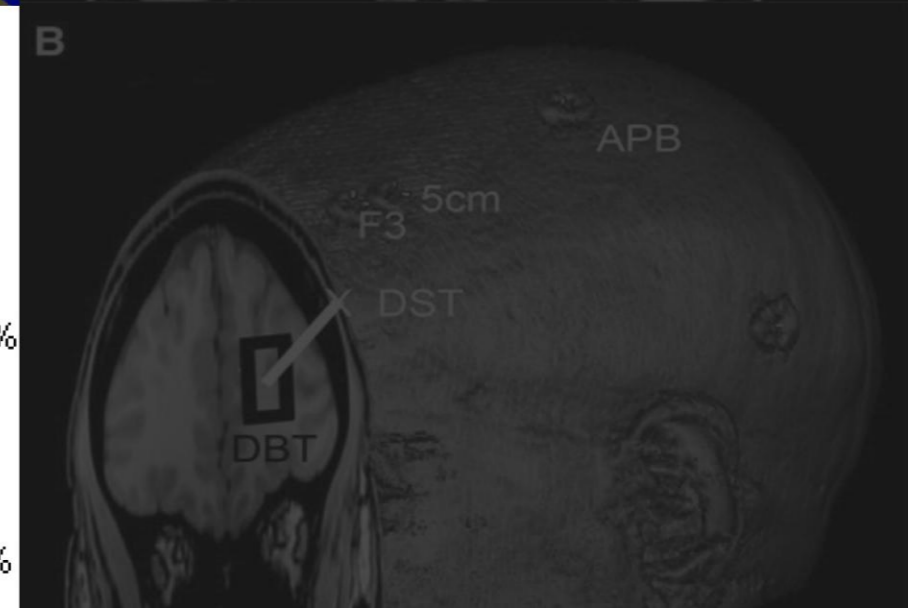
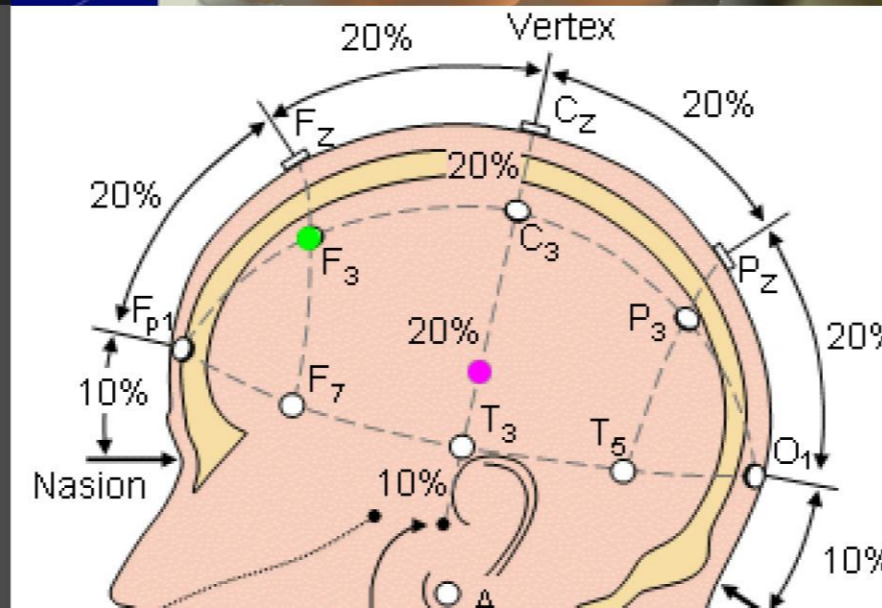
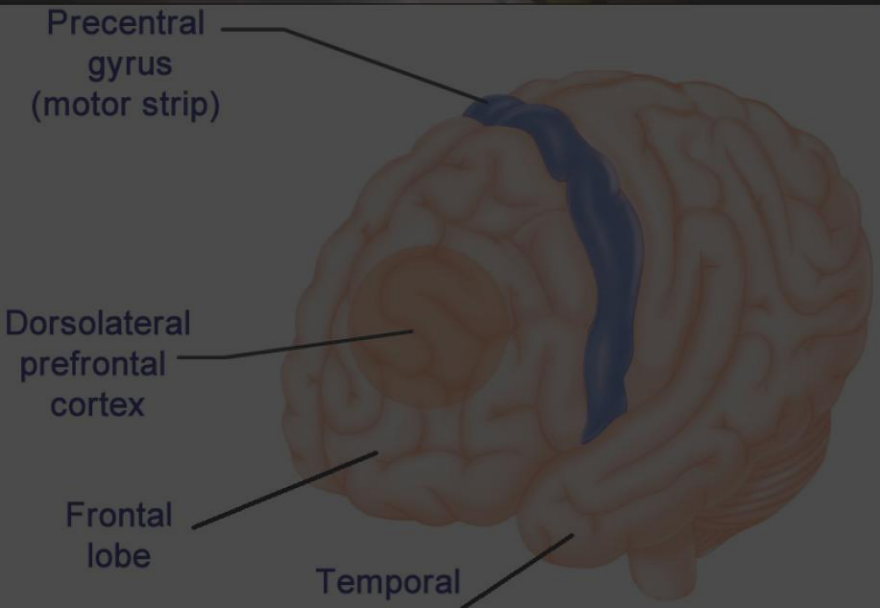
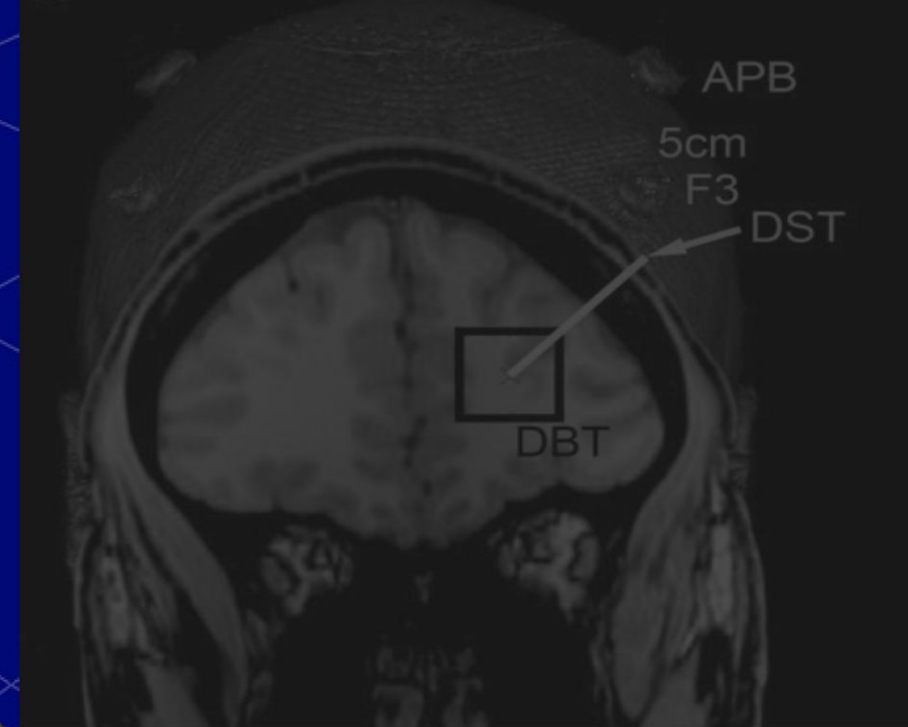
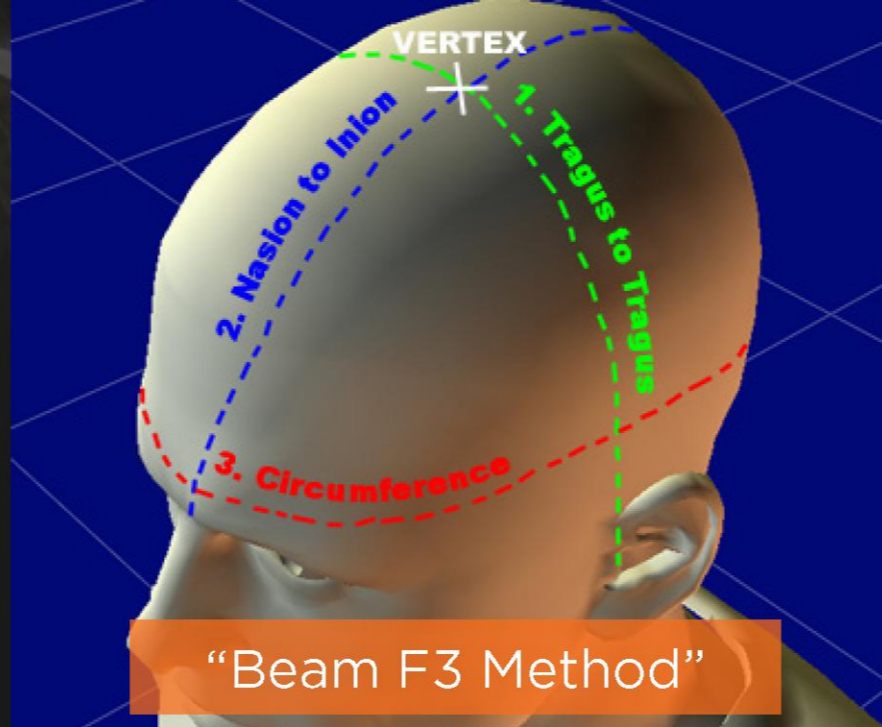


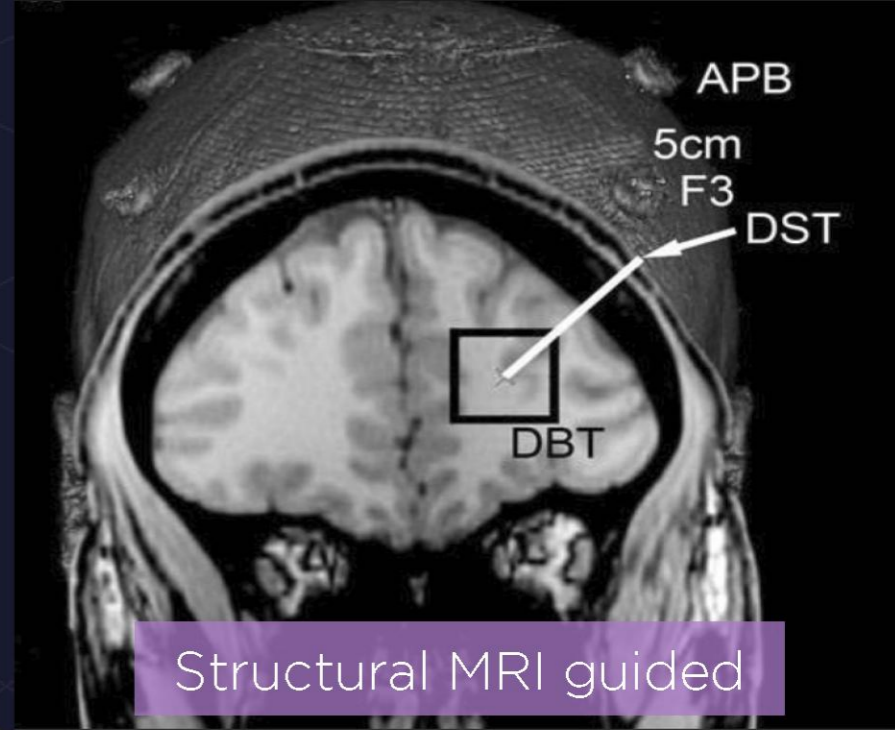
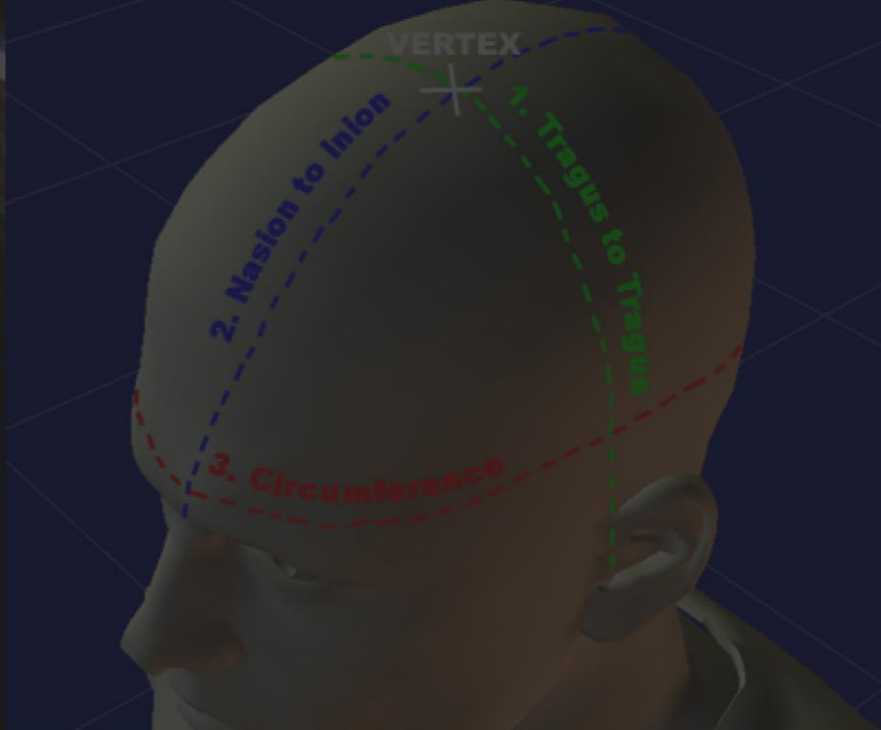
electric field analysis

2 Multielectrode optimization

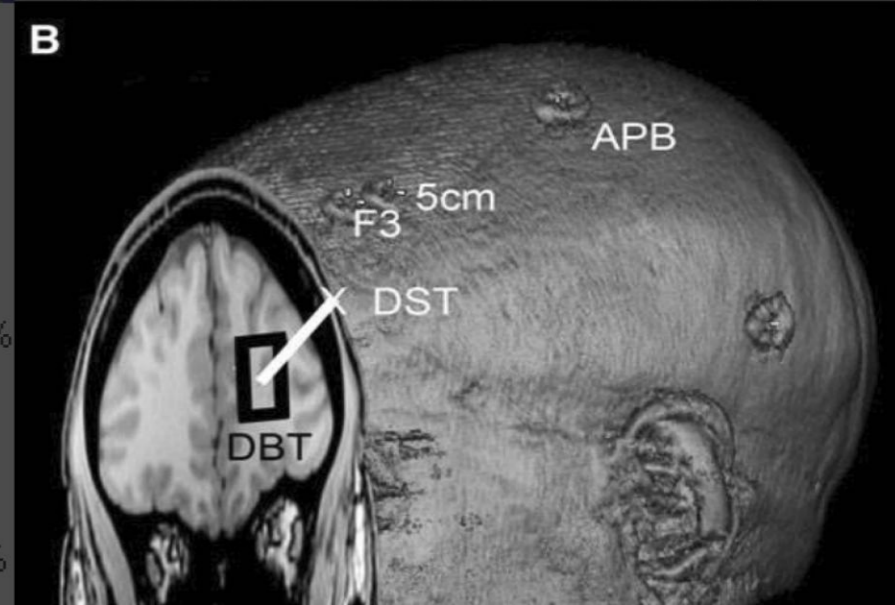
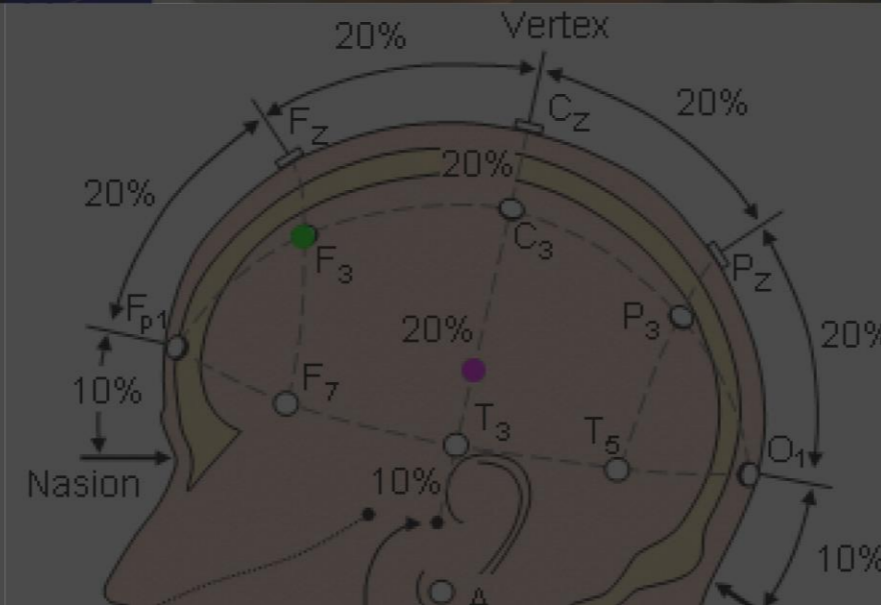
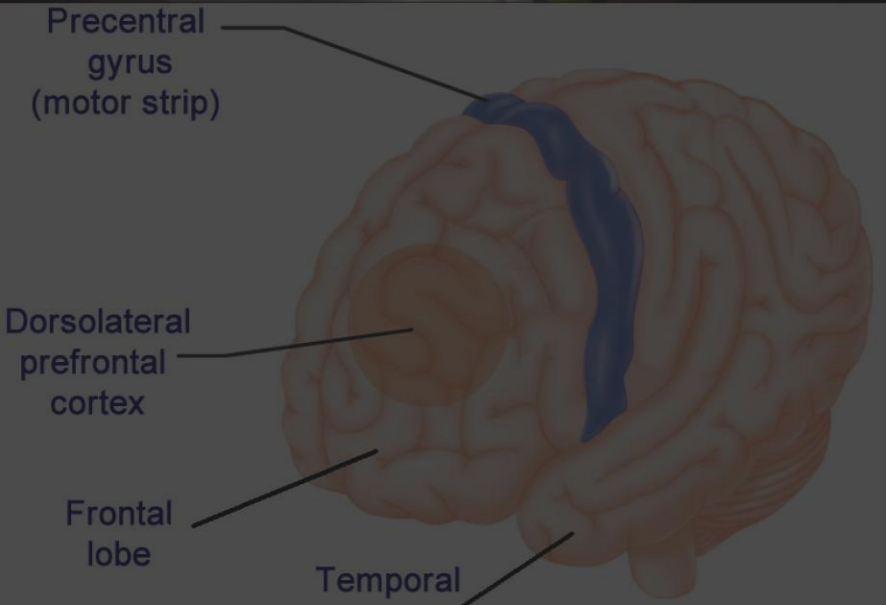


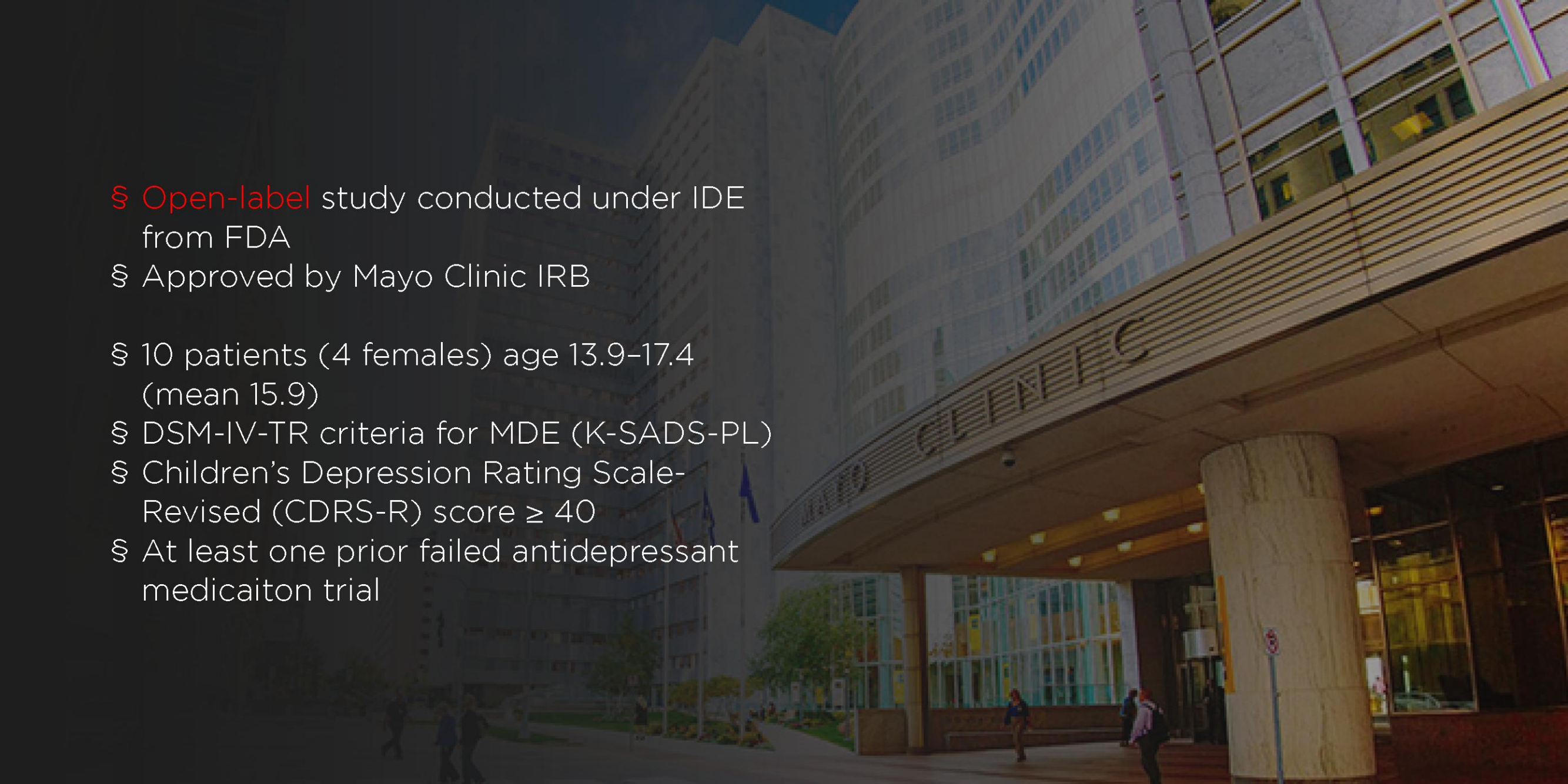






Structural MRI guided



The background of the slide is a photograph of the Mayo Clinic building at dusk. The building is a large, modern structure with a curved facade and many windows. The sky is dark, and the building's lights are on, creating a warm glow. The text is overlaid on the left side of the image.

§ **Open-label** study conducted under IDE from FDA

§ Approved by Mayo Clinic IRB

§ 10 patients (4 females) age 13.9–17.4 (mean 15.9)

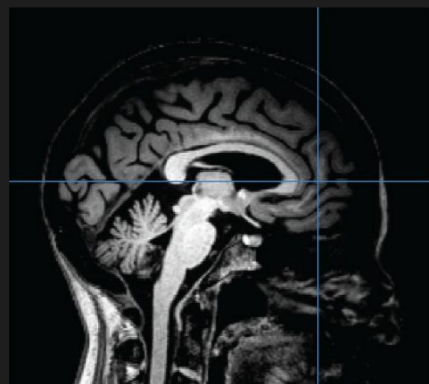
§ DSM-IV-TR criteria for MDE (K-SADS-PL)

§ Children's Depression Rating Scale-Revised (CDRS-R) score ≥ 40

§ At least one prior failed antidepressant medication trial



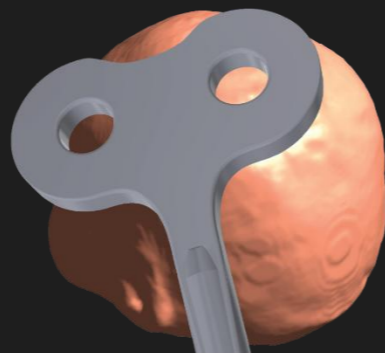
- § Individual left DLPFC target localized using structural MRI (DLPFC Scalp Target: DST)
- § 10-Hz rTMS delivered using NeuroStar Therapy System, at intensity of 120% Standard Motor Threshold
- § 5 days per week, over 6–8 weeks, up to 30 sessions
- § Computational electric field modeling...



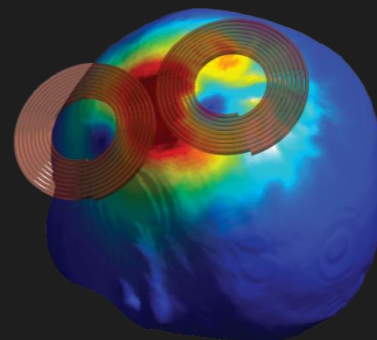
individual MRI



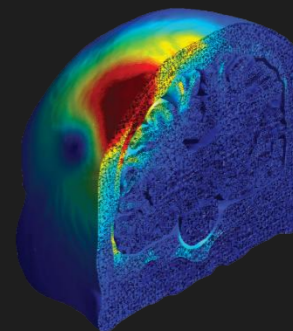
tissue segmentation



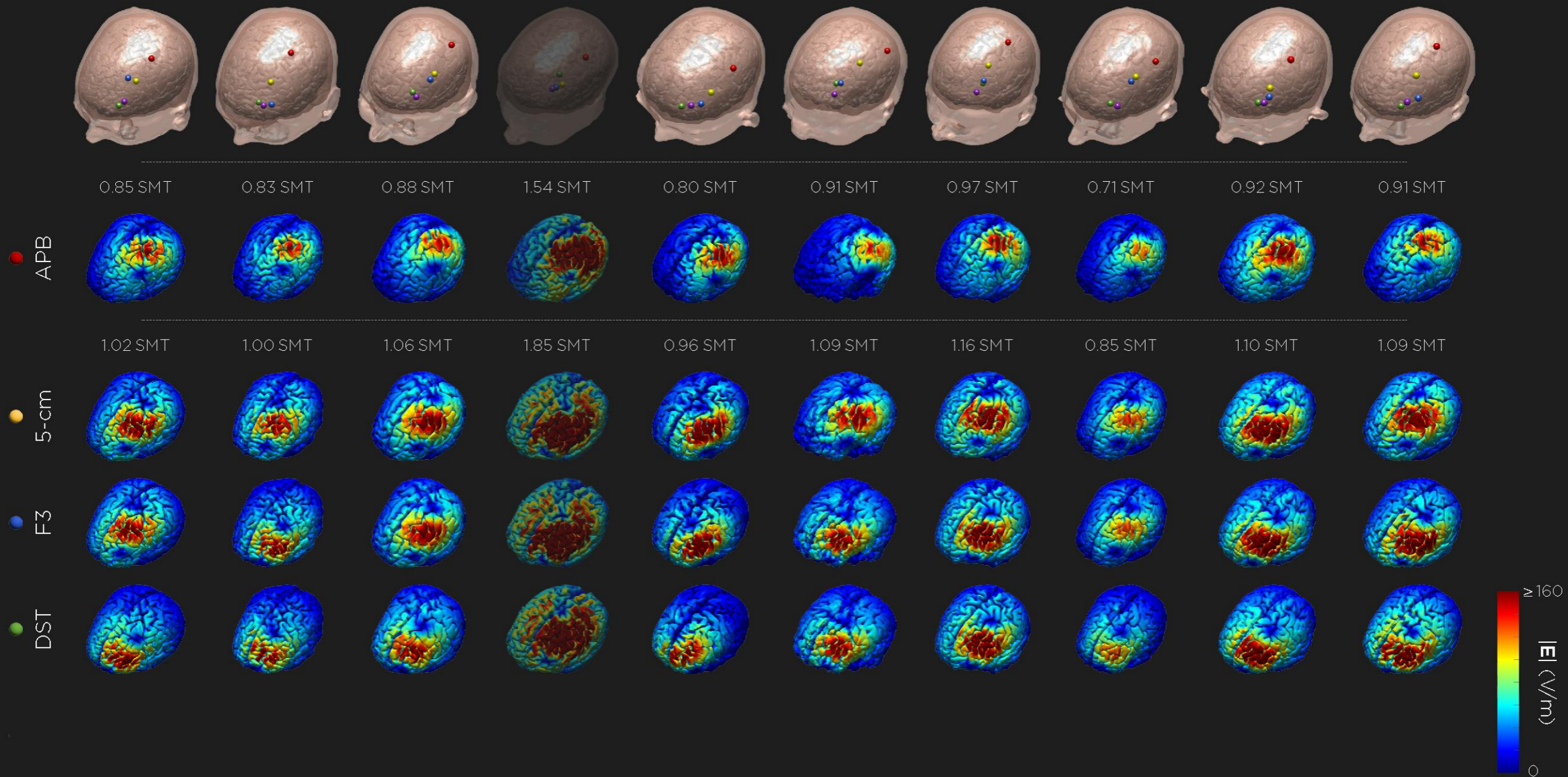
3D head model &
coil model

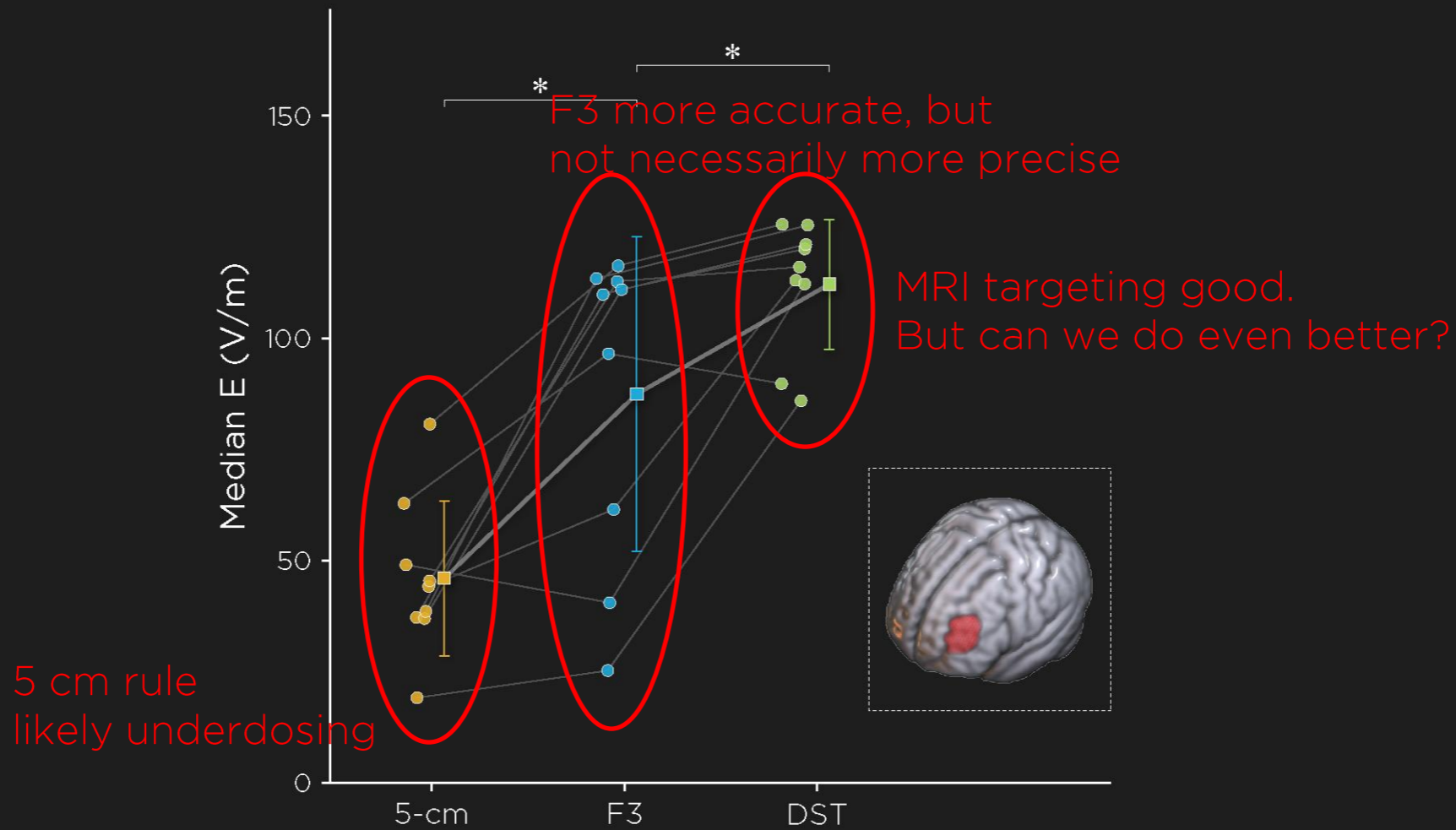


finite element solver



electric field analysis







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 Ojeda CJ, Hager BW, Vakhtin AA and
 Abbott CC (2023) Electric field distribution
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Front. Psychiatry 14:1215093.
 doi: 10.3389/fpsy.2023.1215093

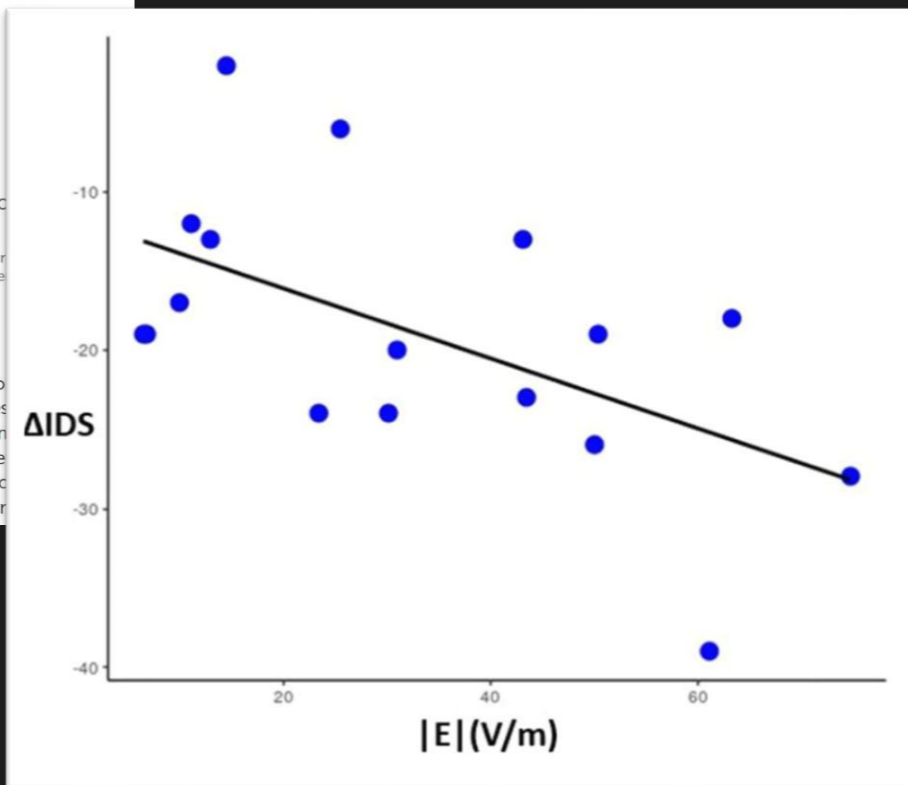
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 Olmstead, Yang, Price, Bowers-Wu, Durham,
 Hazlewood, Farrar, Miller, Lloyd, Garcia, Ojeda,

Electric field distribution predicts efficacy of accelerated intermittent theta burst stimulation for late-life depression

Davin K. Quinn^{*k}, Joel Upston¹, Thomas R. Jones¹, Benjamin C. Gibson², Tessa A. Olmstead¹, Justine Yang¹, Allison M. Price³, Dorothy H. Bowers-Wu¹, Erick Durham⁴, Shawn Hazlewood¹, Danielle C. Farrar¹, Jeremy Miller¹, Megan O. Lloyd¹, Crystal A. Garcia¹, Cesar J. Ojeda¹, Brant W. Hager¹, Andrei A. Vakhtin⁵ and Christopher C. Abbott

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Introduction: Repetitive transcranial magnetic stimulation (rTMS) is a proven intervention for late-life depression (LLD) but may have lower rates of response and remission owing to age-related brain changes. In particular, rTMS electric field strength may be attenuated by cortical atrophy in the prefrontal cortex. To identify clinical characteristics and treatment parameters associated with response, we undertook a pilot study of accelerated fMRI-guided intermittent theta burst stimulation (ITBS) for LLD. We hypothesized that electric field distribution (EFD) would predict efficacy of ITBS. We found that EFD predicted efficacy of ITBS for LLD. This finding suggests that EFD may be a useful clinical characteristic for identifying patients who may benefit from ITBS for LLD.

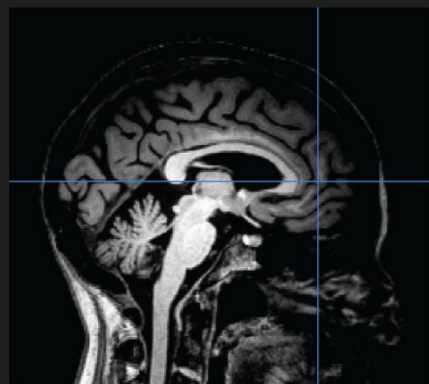


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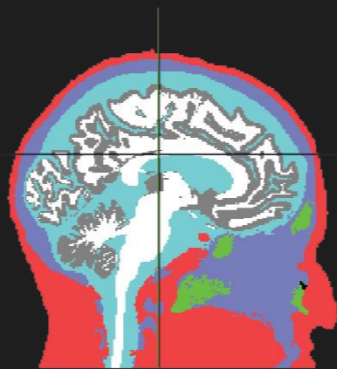
an |E|

110

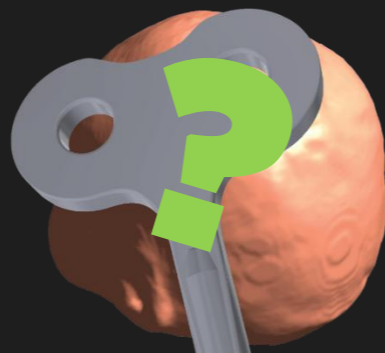
120



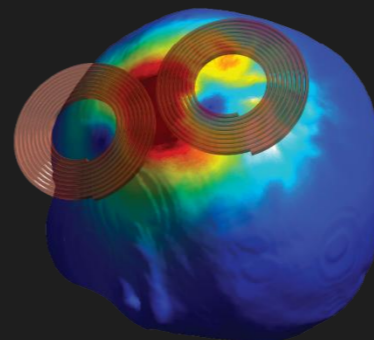
individual MRI



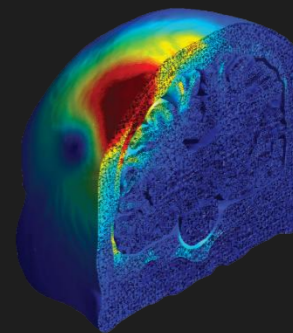
tissue segmentation



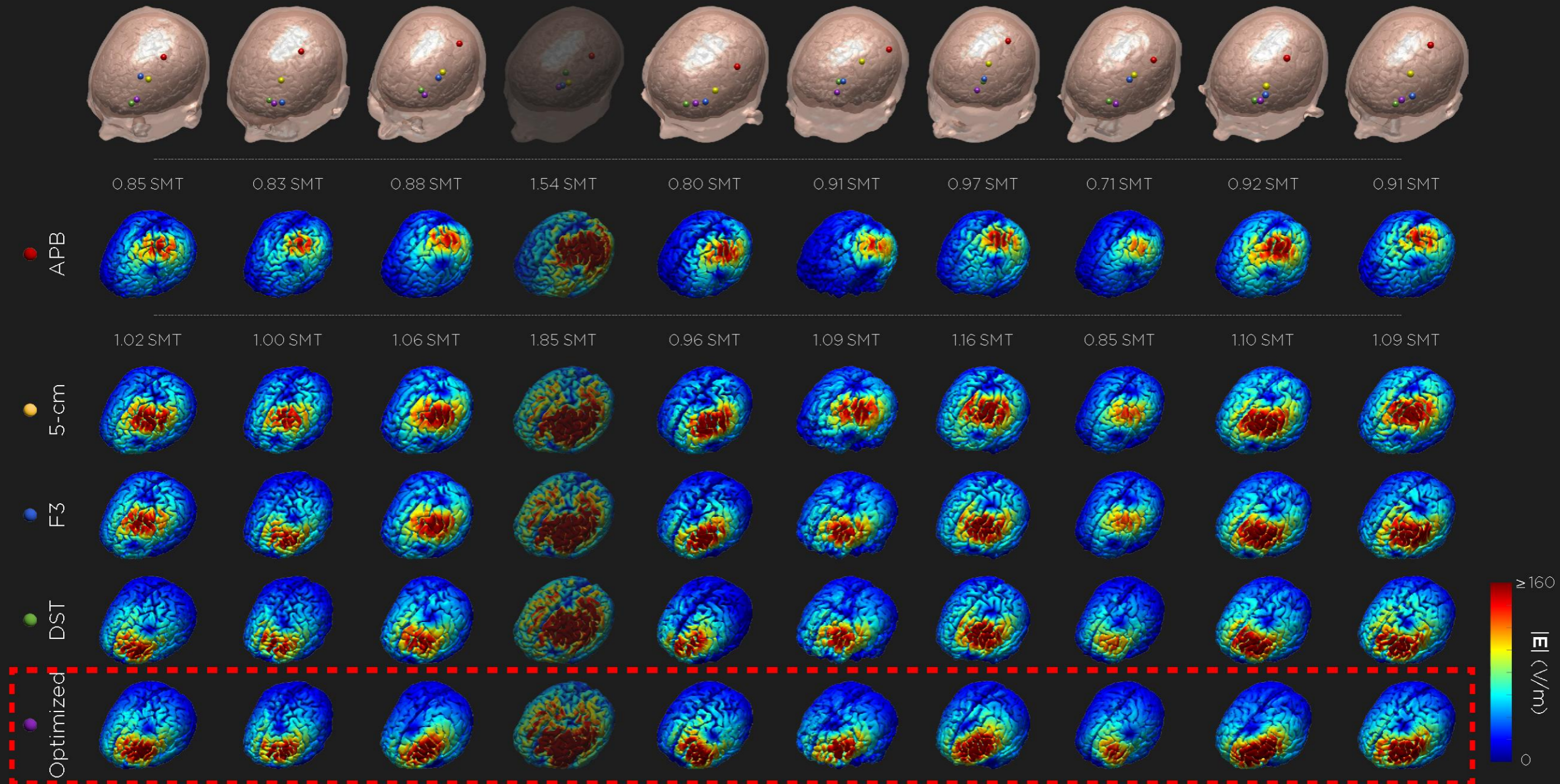
3D head model &
coil model

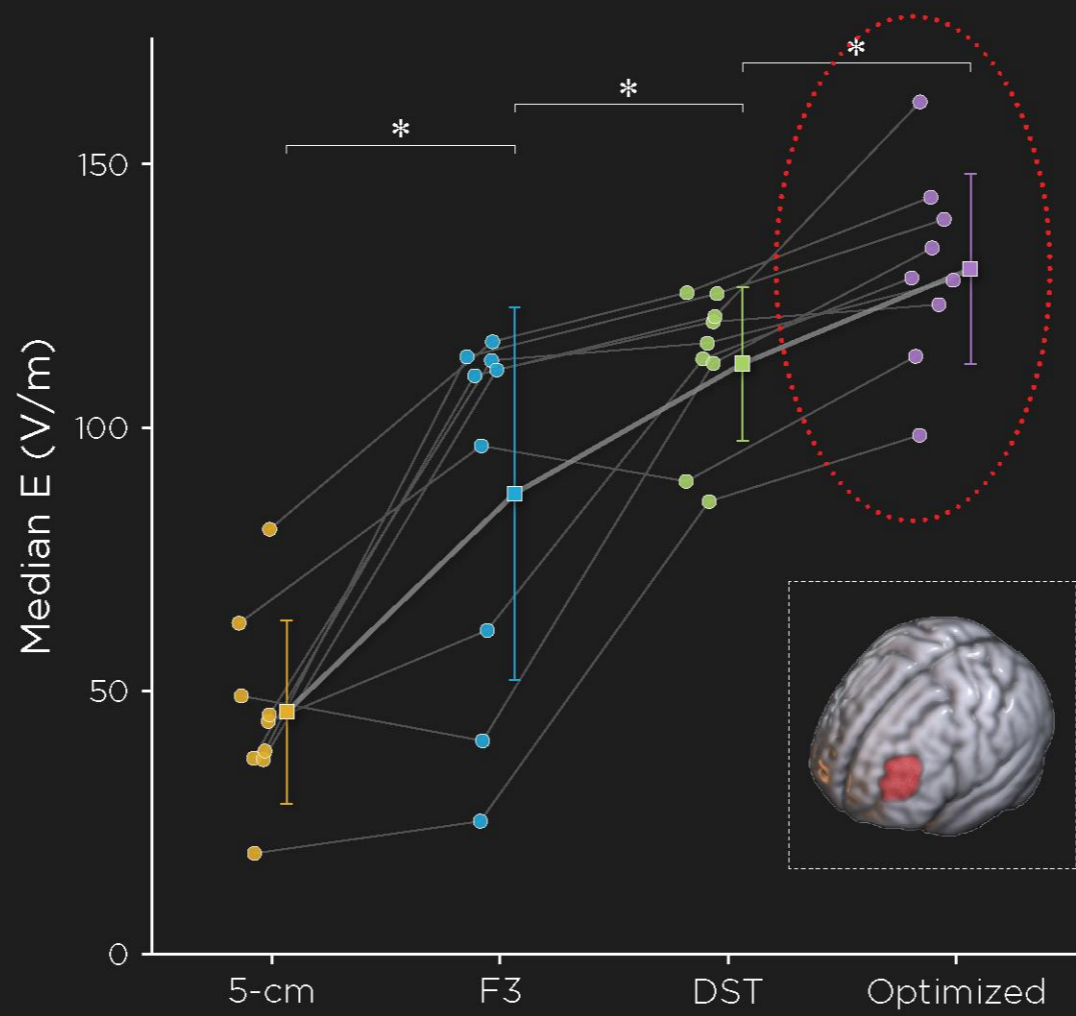


finite element solver



electric field analysis







Device-Facing



Preclinical & Mechanistic



Human & Clinical

1

Evaluate Devices

Compare focality, depth of penetration, and field strength across coil designs on realistic head models

3

Quantify Preclinical Dose

Translate animal/in vitro parameters into human-equivalent field strengths, enabling cross-species inference

5

Benchmark Technique

Verify control conditions deliver negligible cortical field, ruling out unintended active stimulation in blinded trials

2

Inform New Devices

Optimize coil geometry, winding patterns, and pulse waveforms in silico before committing to hardware prototypes

4

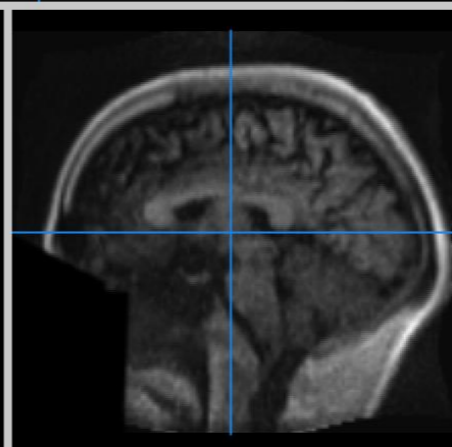
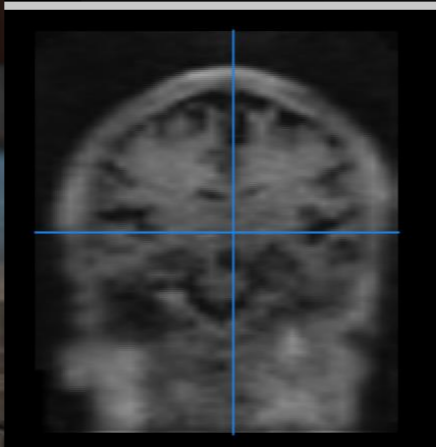
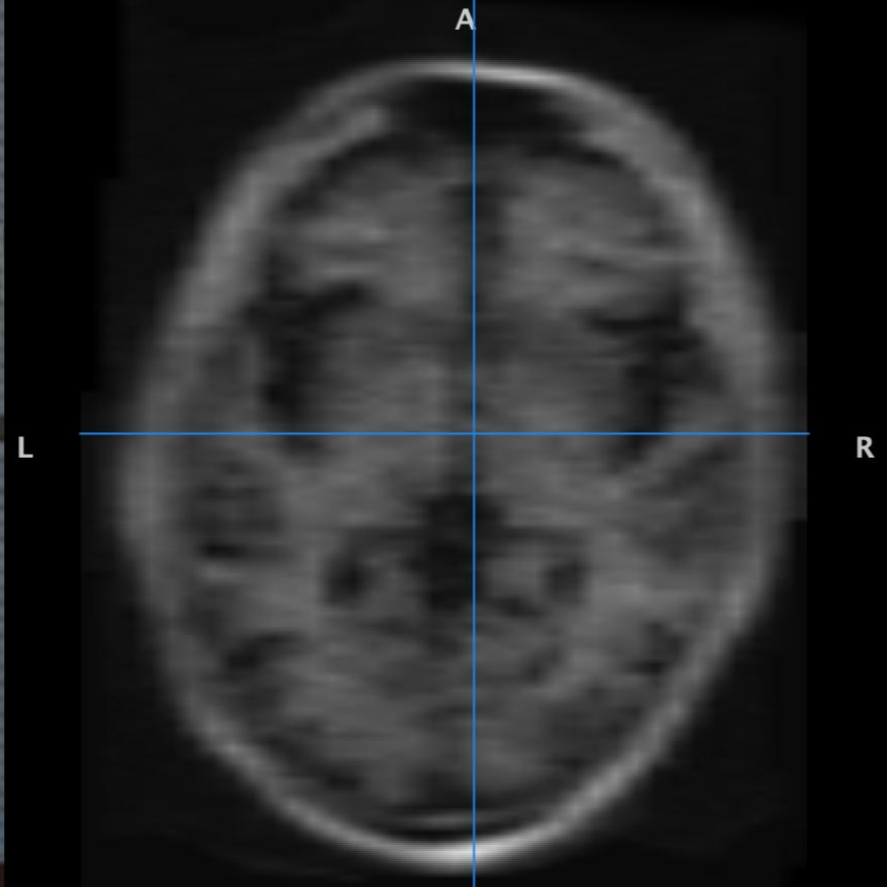
Study Mechanism

Couple macroscopic field models to neuronal ultrastructures to predict activation site and threshold

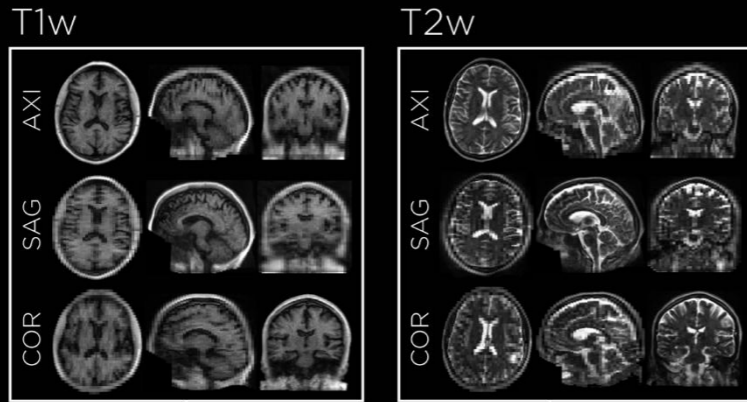
6

Individualize Dosing

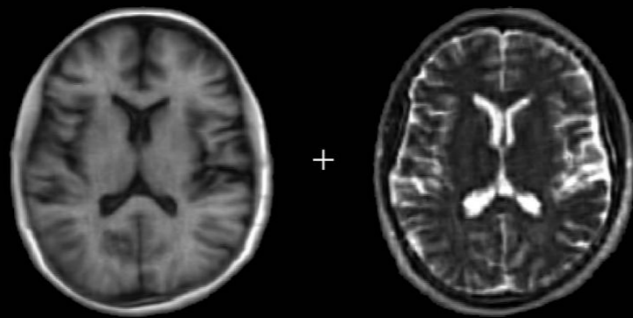
Adjust intensity and targeting per subject based on head anatomy, skull thickness, and target location, moving beyond % machine output



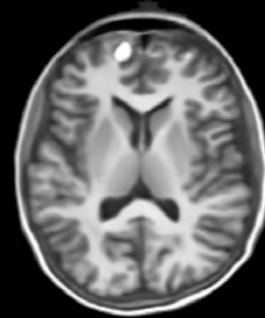
64 mT



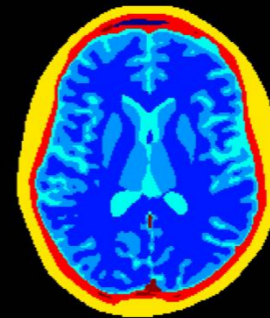
MRR (ANT)



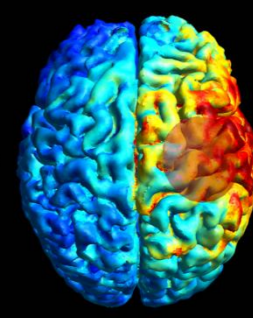
SynthSR



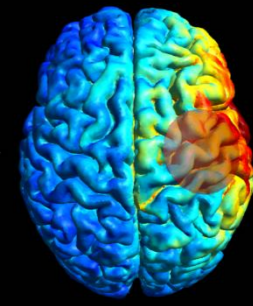
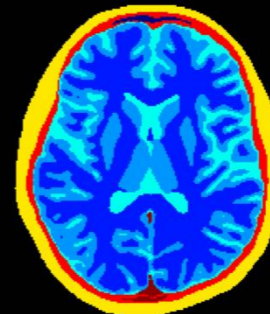
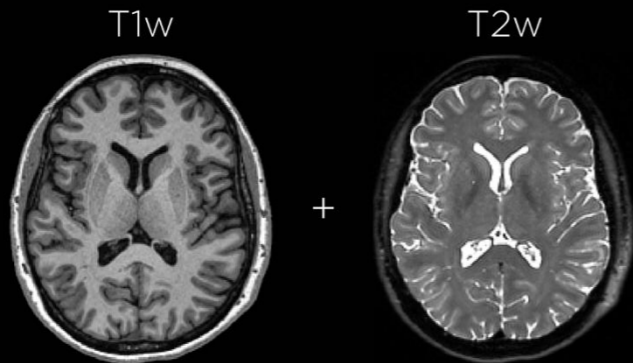
Segmentation
(Freesurfer/SimNIBS)

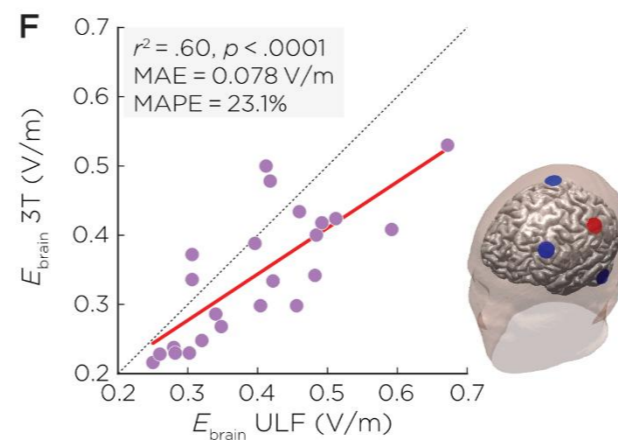
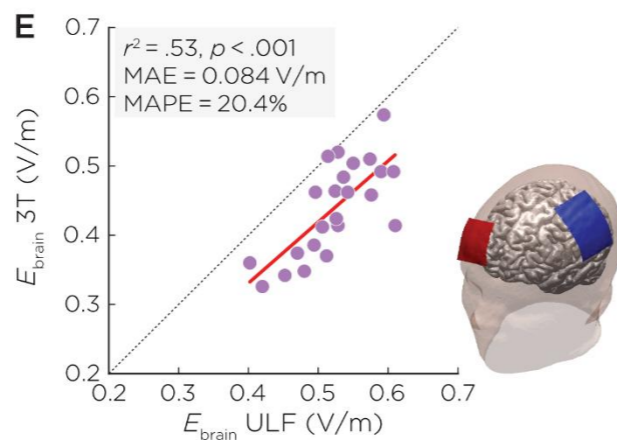
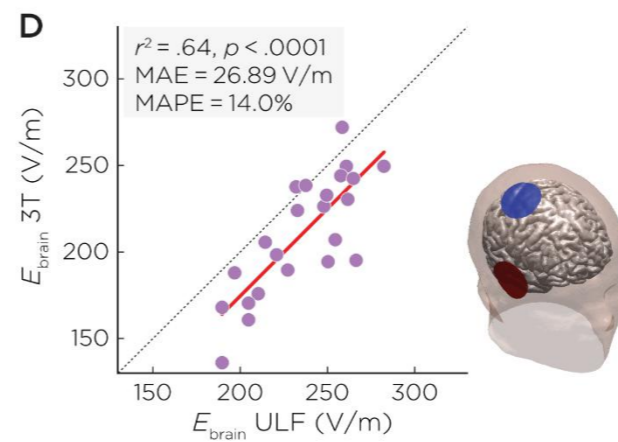
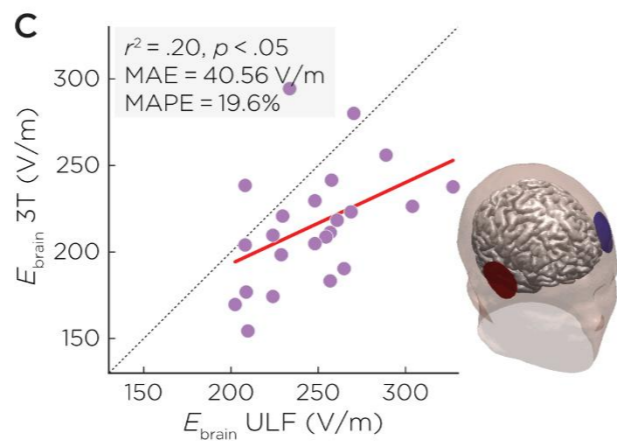
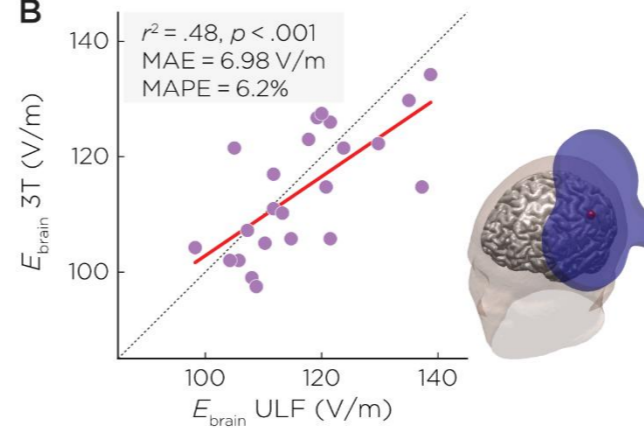
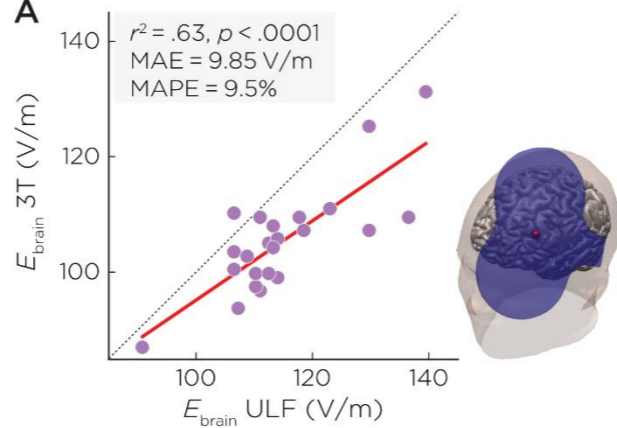


E-field
(SimNIBS)



3T







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