Measurements and models of electric fields in the in vivo human brain during TES

Poster Number:

2613

Submission Type:

Abstract Submission

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Introduction:

Transcranial electric stimulation (TES) aims to stimulate the brain by applying weak electrical currents at the scalp (Ruffini et al., 2013). However, the magnitude and spatial distribution of electric fields in the human brain are unknown. Despite increasing sophistication in the computational models for TES, none of them have been directly validated to-date. Here we aim to address this with in vivo intracranial recordings in humans by directly measuring field intensities produced by TES at the cortical surface and deeper brain areas.

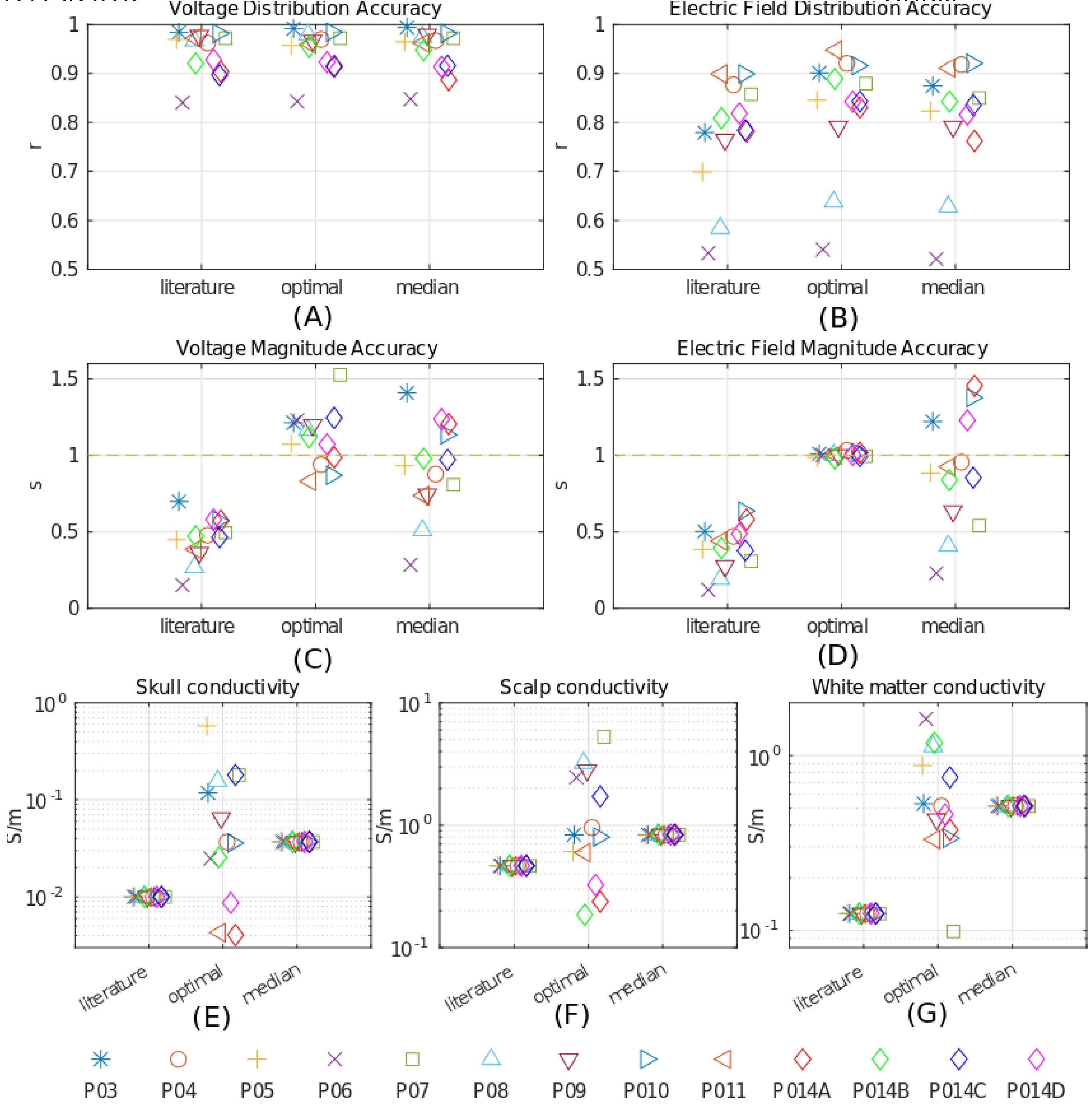
Methods:

Electric potentials were recorded intracranially from ten patients undergoing invasive monitoring for epilepsy surgery, with subdural grids, strips, and depth electrodes. These recordings were then compared to various detailed computational models, including differential conductivity between skull spongiosa and compacta, and white matter anisotropy. Models were also calibrated using the recordings to minimize the difference between measurements and model predictions. In doing so, we obtain calibrated models that conclusively answer outstanding questions about stimulation magnitudes, spatial distribution, and modeling choices.

Results:

A summary of the model validations is shown in Figure 1. The distribution accuracy is indicated by the correlation r between recorded and model-predicted values, and magnitude accuracy by the slope s of the best linear fit with predicted value as "independent" and measurement as "dependent" variables. Conductivities reported in the literature used in existing models tend to overestimate the voltages and electric field magnitudes (Figure 1CD under "literature"). The measured voltages are tightly correlated with the predicted electric potentials (Figure 1A). The correlation of predicted and measured electric fields is lower than for the raw potentials (Figure 1B), as the calculated field is the difference of two close-by measurements, each with some inherent noise. The best fitted conductivity values vary across individuals (Figure 1EFG). The median of these optimal conductivities differ from the literature values, but are largely in the same proportions. Compared to models using literature conductivities, the models with median values across subjects give significantly better accuracy in terms of predicting the electric field distribution and the magnitude (Figure 1BD).

Figure 2A--E shows the recorded data and the predictions from the calibrated head model for one subject. When collapsing all recordings across subjects (Figure 2FG) we find correlation between measured and predicted field projections of r=0.89 and r=0.84 for cortical and depth electrodes respectively.


Voltage Distribution Accuracy
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(A)
Electric Field Distribution Accuracy
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1
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0.8
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(D)
Skull conductivity
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optimal
median
(E)
Scalp conductivity
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10^0
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literature
optimal
median
(F)
White matter conductivity
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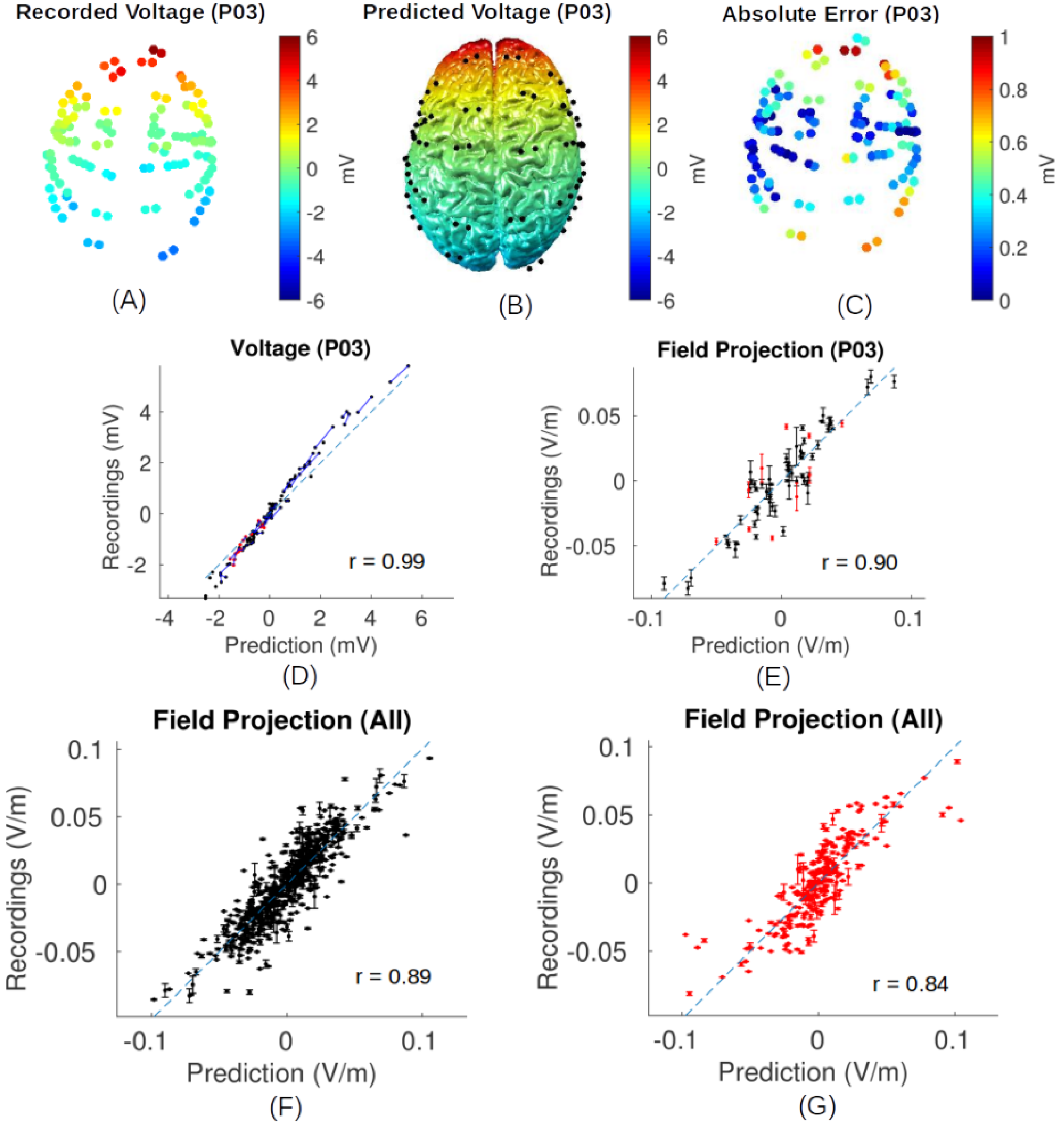
·Figure 1



·Figure 2

Conclusions:

Our main finding is that the intensities of electric field reach 0.4 V/m when using 2 mA transcranially. This is approximately half as strong as previous predictions using computational models (Datta et al., 2009). Peak intensities are achieved underneath the stimulation electrodes, but also in deep midline structures such as the anterior cingulate and the peri-ventricular white matter for the specific configurations tested here. We find that individualized models provide predictions of the spatial distribution of currents with an accuracy of r=0.89 for cortical electrodes and r=0.84 for depth electrodes when pooling data across all subjects. These models capture individual anatomy for brain, CSF, skull, air cavities and skin at 1 mm^3 resolution. Including variables such as anisotropic white matter and inhomogeneous bone compartments does not improve prediction performance. But extending the FOV to include the entire head and neck significantly improves prediction accuracy. This is the first study to validate and calibrate current-flow models with in vivo intracranial recordings in humans, providing a solid foundation to target stimulation and interpret clinical trials.

Brain Stimulation Methods:

Non-invasive Electrical/tDCS/tACS/tRNS [1]
TDCS

Imaging Methods:

Anatomical MRI [2]
Diffusion MRI

Modeling and Analysis Methods:

Segmentation and Parcellation

Keywords:

Computing
Data analysis
ELECTROCORTICOGRAPHY
Modeling
MRI
Segmentation
STRUCTURAL MRI

[1|2]Indicates the priority used for review

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Please indicate which methods were used in your research:

Structural MRI
Diffusion MRI
Computational modeling

Which processing packages did you use for your study?

SPM
FSL

Provide references in author date format

Datta, A. (2009), 'Gyri-precise headmodel of transcranial DC stimulation: Improved spatial focality using a ring electrode versusconventional rectangular pad', Brain stimulation, vol. 2, no. 4, pp. 201–207
Ruffini, G (2013), 'Transcranial current brain stimulation (tCS): models and technologies', IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 21, no. 3, pp. 333–345