Current Density Weighted Indices for Correspondence between fMRI with Electrocortical Stimulation Maps

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Introduction: In surgical treatment of brain lesions, the gold standard for presurgical brain mapping is subdural electrocortical stimulation (ECS), which is an invasive procedure. Functional MRI (fMRI), a non-invasive technique, may be a plausible alternative if it can be shown that fMRI and ECS activation maps are spatially consistent. There are indications that the level of elicited neuronal activation is influenced by applied electrical stimulus levels [1], and thus, an ECS-fMRI correspondence index that incorporates current density map information may be physically more meaningful then Euclidean distance based indices [2,3]. This work formulates a 3D current density weighted method to measure ECS-fMRI correspondence for our clinical ECS-fMRI mapping procedure (Fig. 1). Euclidean distance information between activated voxels and ON/ OFF electrode pairs is embedded in current density maps obtained by solving the Laplace equation for a quasistatic volume conductor using the finite difference method [4]. Each current density map is unique to each patient-task combination and depends solely on the ECS map geometry and current/ voltage stimulation parameters. The proposed current density weighted indices were evaluated for nine simulated and three patient datasets.

Theory: In ECS, the brain can be modeled as a volume conductor with no enclosed electrical charges. For each stimulated electrode pair, a quasistatic condition is assumed and the scalar potential field, $\Phi(\boldsymbol{r})$, is computed by solving the Laplace equation using the Gauss Seidel algorithm. The required boundary conditions include the applied voltage levels at the electrode-brain interfaces (Dirichlet) and knowledge that the first derivative of the scalar potential perpendicular to the brain surface is zero (Neumann). The current density maps are then evaluated from $\Phi(\boldsymbol{r})$ with Ohm's law. Fig. 2 shows simulated current density magnitude contour plots.

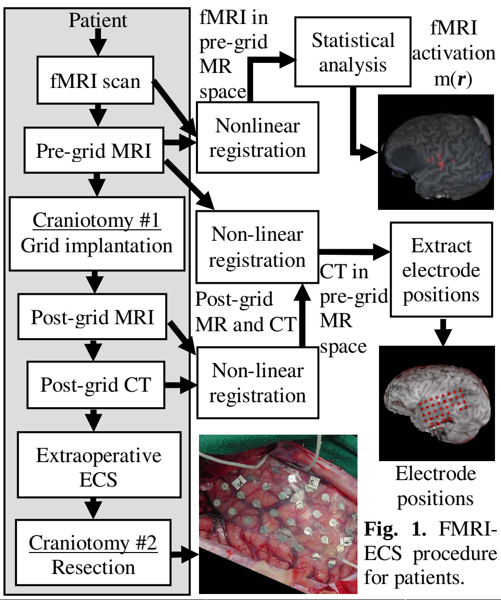

Fig. 1. FMRI-ECS procedure for patients.

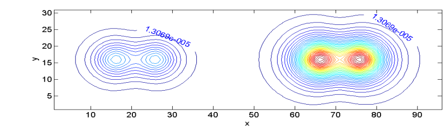

Fig. 2. Current density contour plot (6 mm below simulated electrodes) for stimulus levels 0.6V (left) and 2V (right). Display ranges for both plots are the same

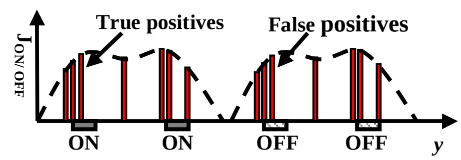

Fig. 3. FMRI activated voxels (vertical bars) weighted by ON and OFF electrodes' current density (dotted lines) at the voxels' locations contribute to *TP* and *FP* quantities respectively.

To compute current density weighted sensitivity, specificity, and geometric mean (*gmean*) [5] indices for a pair of ECS-fMRI maps, the weighted number of fMRI voxels that are true positives (*TP*), false positives (*FP*), true negatives (*TN*) and false negatives (*FN*) must first be defined. Each fMRI map, denoted by $m(\boldsymbol{r})$ is spatially registered to a CT dataset (Fig. 1) from which the electrodes' positions are extracted. Let $J_{ON,k}(\boldsymbol{r})$ denote the 3D current density map when the k^{th} pair (of K pairs) of ON electrodes is stimulated. For good ECS-fMRI correspondence, fMRI activation should occur near ON electrode pairs and not near OFF electrode pairs. The weighted number of *TP* is computed by multiplying each fMRI activated voxel (value of 1) with the current density at that voxel for each ON electrode pair, and then summing all weighted voxels such that $TP = \sum_{k=1}^{K} \sum_{\boldsymbol{r}_i \in FOV} m(\boldsymbol{r}_i) J_{ON,k}(\boldsymbol{r}_i)$, where $\boldsymbol{r}_i=(x_i, y_i, z_i)$ for the i^{th} voxel, and FOV denotes the imaging field of view. An activated voxel that is far away from any ON electrode pair is effectively ignored since the corresponding current density value will be negligible. Similarly, *FP* is computed by using $J_{OFF,l}(\boldsymbol{r})$, the current density map when the l^{th} pair (of L pairs) of OFF electrodes was stimulated $FP = \sum_{l=1}^{L} \sum_{\boldsymbol{r}_i \in FOV} m(\boldsymbol{r}_i) J_{OFF,l}(\boldsymbol{r}_i)$. *TN* and *FN* are computed with

$$TN = \sum_{l=1}^{L} \sum_{\boldsymbol{r}_i \in FOV} (1-m(\boldsymbol{r}_i)) J_{OFF,l}(\boldsymbol{r}_i) \quad \text{and} \quad FN = \sum_{k=1}^{K} \sum_{\boldsymbol{r}_i \in FOV} (1-m(\boldsymbol{r}_i)) J_{ON,k}(\boldsymbol{r}_i),$$

respectively, where $1\text{-}m(\boldsymbol{r}_i)$ is 1 for non-activated voxels and 0 for activated voxels. Fig. 3 illustrates the equations for *TP* and *FP* in one dimension. The current density weighted indices (all in the range of 0 to 1.0) can be then be evaluated with *sensitivity=TP/(TP+FN)*, *specificity=TN/(TN+FP)*, and *gmean*= $\sqrt{sensitivity \cdot specificity}$.

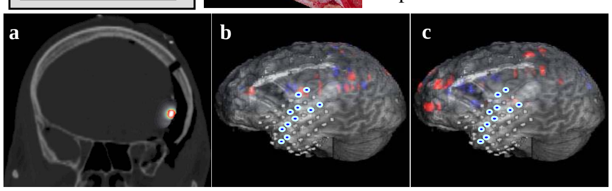

Fig. 4. Patient 1 (**a**) coronal view of CT volume with overlaid current density map displayed on a color scale (red indicates higher values). Fused 3D MR, CT electrode grid and fMRI activation datasets (red for fMRI activation) for (**b**) picture naming and (**c**) response naming tasks. Blue circular tags denote ON electrodes.

Methods: A 3D volume with a simulated electrode grid and simulated fMRI maps were used to investigate the behaviors of the proposed current density weighted indices. The indices were also computed for three patients (one of which is reported in Table 1), who participated in fMRI studies for verbalized speech tasks followed by language mapping with extraoperative ECS procedures prior to surgical treatment.

Table 1. Patient 1 ECS-fMRI correspondence indices.

fMRI Task	*sensitivity*	*specificity*	*gmean*
picture naming	0.07	0.98	0.26
response naming	0.01	1.00	0.11

Results: The simulated cases showed that the proposed indices measure ECS-fMRI correspondence consistently in a predictable manner as the fMRI activation moves closer or farther away from the ECS truth. The current density weighted indices are more sensitive to incremental improvements in ECS-fMRI correspondence than a fixed radii method. Figs. 4(b-c) show the fused ECS-fMRI datasets for two language tasks. The picture naming task in Fig. 4(b) has a cluster of fMRI voxels (red) near ON electrodes while Fig. 4(c) does not. The current density weighted sensitivity and *gmean* values in Table 1 reflect the higher ECS-fMRI correspondence for the picture naming task compared to the response naming task.

Discussion: The current density weighted indices provide a principled way to measure 3D ECS-fMRI correspondence with the goal of evaluating fMRI as a tool for defining resection limits. In future work, the technique will be applied to additional patient data and significance tests will be performed for ECS-fMRI correspondence.

Acknowledgements: This research is supported in part by NIH grants 1P01 CA87634 & R01 EB00309.

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