# A co-registration approach for electrocorticogram electrode localization using post-implantation MRI and CT of the head

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Abstract-Electrocorticogram (ECoG) signals are acquired from electrodes that are surgically implanted into the subdural space of the brain. Although this procedure is usually performed for clinical purposes such as defining seizure locations and/or brain mapping, ECoG signals can also be used for characterizing the electrophysiology underlying various behaviors or for brain-computer interface applications. Therefore, defining the anatomical location of ECoG electrodes is an important process for contextual interpretation of the results. Current techniques utilize semi-automated statistical methods to co-register ECoG electrodes from either post-implantation X-rays or computer tomography (CT) images with a preimplantation magnetic resonance imaging (MRI) of the brain. However, due to brain deformation caused by surgical electrode implantation, ECoG electrode locations must be projected onto the brain surface of the pre-implantation MRI, which may result in error. The authors present an exploratory study where post-implantation MRI images were successfully used for co-registration with post-implantation CT images of ECoG electrodes without the need for projection. By using postimplantation CT and MRI images which preserve the brain deformation, error in defining ECoG electrode locations may be reduced or eliminated.

#### I. INTRODUCTION

Electrocorticogram (ECoG) signals are acquired from subdural electrodes that are surgically implanted for clinical purposes such as seizure focus localization or functional brain mapping during neuro-oncological resection procedures. However, ECoG signals can also be used for research purposes such as for characterizing the electrophysiology underlying various behaviors [1] or for brain-computer interface (BCI) applications [2]. In many of these studies, defining the anatomical location of each ECoG electrode is critical to providing contextual meaning to the results. Identifying ECoG electrode locations has often been accomplished by co-registering a set of pre-implantation magnetic resonance images (MRI) with either a computed tomography (CT) or X-ray of the post-implantation head [3], [4]. These techniques use the pre-implantation MRI as the source of brain

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anatomical data and the post-implantation CT or X-ray as the source of the ECoG electrodes' locations. A combination of manual and semi-automated statistical image processing techniques are then used to perform this co-registration. Surgical implantation of ECoG electrodes often creates a deformation of brain tissue due to factors such as foreign body mass effect, swelling, and pneumocephaly, leading these techniques [3], [4] to rely on projection to place electrodes onto the surface of a pre-implantation brain instead of a post-implantation brain. However, since electrodes on the post-implantation CT tend to exist "beneath" the cortical surface seen on the pre-implantation MRI, the raising of the ECoG electrodes onto the cortical surface by projection may ultimately alter their true anatomical location. While this technique estimates co-registration error as relatively small [3] (up to 6.8 mm), this level of deviation may, in some cases, mean the difference between an electrode being localized anterior or posterior to the central sulcus. Hence, approaches for ECoG co-registration that account for post-implantation brain deformation may be necessary.

To preserve the post-implantation brain deformation, it is necessary to use a post-implantation MRI as the source of brain anatomical data. Using post-implantation MRI, however, presents a unique set of challenges. For example, ECoG electrode implantation introduces abnormalities and artifacts, such that automated MRI brain segmentation methods relying on standard brain maps for voxel-based morphometry (e.g. Statistical Parametric Mapping (SPM) analysis environment) cannot be used. In addition, although post-implantation MRI sequences such as gradient echo may provide good images of ECoG electrodes, acquiring these sequences at high 3D resolution, which is necessary for electrode localization, is not a standard procedure in clinical post-implantation scans. Hence, co-registration of post-implantation MRI and CT scans is still required to identify ECoG electrode locations. However, this co-registration is not amenable to automated techniques due to abnormalities introduced by the ECoG electrode implantation. To address these problems, the authors combined standard neuro-imaging tools to devise an alternative method for localizing ECoG electrodes through co-registration of a post-implantation MRI and CT of the head.

#### II. METHODS

# A. Overview

In this proof-of-concept study, the co-registration of postimplantation MRI and CT scans of the head was accomplished by a combination of automated and manual techniques. The brain was first segmented from the postimplantation MRI with an automated technique that does not rely on standard brain maps. This image was then coregistered with the CT scan through a series of user-guided rigid body transformations. After the coordinate spaces of the post-implantation MRI and CTs were aligned, the electrodes were manually segmented from the CT scan. These electrodes were then merged with the post-implantation MRI to form a new 3D image set. This new image set was then rendered in 3D in order to visualize the ECoG electrode positions.

### B. Subjects

The study was approved by the Institutional Review Boards of the University of California, Irvine, and the Rancho Los Amigos National Rehabilitation Center. Subjects were recruited from a population of epilepsy patients undergoing temporary ECoG electrode implantation for seizure localization. They underwent 3D post-implantation MRI and CT scans for clinical purposes.

#### C. MRI Brain Segmentation

Brain segmentation was performed using the Brain Extraction Tool (BET) from the Functional MRI of the Brain Software Library (FSL) imaging analysis environment [5]. BET applies an evolving deformable model to automatically outline the 3D surface of the brain, while excluding the noise created by the ECoG electrodes. Upon successful segmentation, the images were saved and will be referred to as the *segmented brain MRI* in the remainder of the paper.

### D. MRI and CT Co-registration

Co-registration is necessary to align the *segmented brain MRI* and the post-implantation CT scan. Although mutual information co-registration tools exist for normal brains in analysis environments such as SPM, the presence of abnormalities after implantation often results in failure of these approaches. Here, manual co-registration was performed by overlaying the *segmented brain MRI* on top of the CT scan of the head using the Multi-image Analysis GUI (Mango) software [6]. The CT scan was then subjected to manual rigid body transformations until it matched various brain structures in the *segmented brain MRI* (e.g. lateral ventricles, corpus callosum, pons, and the fourth ventricle). The transformation was saved to generate a new image set, which will be later referred to as the *transformed head CT*.

### E. ECoG Electrode Segmentation

After successful co-registration of the MRI and CT scans, the electrodes from the *transformed head CT* were manually segmented from the remainder of the scan using the MRICron software [7]. The centers of the 3D volumes of interest (VOI) containing each of the ECoG electrodes were manually defined. Based on the size of the ECoG electrodes, a VOI diameter of 4 mm was chosen using default edge detection parameters. The remainder of the CT scan was then discarded, thereby generating a new image set containing only the ECoG electrodes. This image set will be referred to as the *segmented electrodes CT* in the remainder of the paper. Also, note that this method retains the co-registration transformations.

### F. MRI Head and CT Electrode Merging

Since the *segmented brain MRI* and the *segmented electrodes CT* have matching coordinates, they were simply overlayed on top of each other in the Mango analysis environment. The two images were subsequently merged to form a single *MRI-CT image*.

## G. 3D Rendering

The *MRI-CT image* was rendered in 3D using MRICron. Note that rendering can also be performed in a number of other medical imaging viewers that support 3D rendering. A commercial desktop publishing software can then be used to create labels for each of the electrodes.

### III. RESULTS

Two subjects undergoing ECoG electrode implantation for epilepsy surgery evaluation were recruited to participate in the study. Subject 1 was a 22 year old male with a history of intrauterine stroke resulting in porencephaly of the left pre-frontal lobe. Subject 2 was a 28 year old female with cystercircosis. For both subjects, their post-implantation 3D MRI and CT scans were taken within hours of one another; hence, it is assumed that the degree of brain deformation was identical during both scans. Fig. 1 illustrates representative results (Subject 1) from the MRI and CT image processing workflow described in Section II. As seen in Fig. 1A, the FSL BET tool (see Section II-C) was able to successfully segment the brain in spite of significant abnormalities. These abnormalities include not only those caused by ECoG electrodes, but also those caused by the left frontal porencephaly. However, some grey matter loss during the segmentation process is apparent, particularly in the right pre-frontal lobe and the cerebellum (see Fig. 1B). Nevertheless, much of the cerebral cortex was unaffected, and anatomical landmarks such as the tentorium, ventricular system, and brainstem (particularly the pons), were adequately preserved to facilitate successful coregistration (see Section II-D). Finally, note that skewing and scaling were not required to achieve a reasonable match in co-registration.

Fig. 1C shows the results of the successful electrode segmentation (see Section II-E). These electrodes were then merged with the *segmented brain MRI* (see Fig. 1D), and appear on the brain cortical surface without projection (Section II-F). Figs. 2 and 3 illustrate the final result (Section II-G) for both Subjects 1 and 2, respectively.

### IV. DISCUSSION

The preliminary results indicate that using postimplantation MRI as the source of brain anatomical data for MRI-CT co-registration to localize ECoG electrodes is feasible. As demonstrated in the Fig. 1D, merging the *segmented electrode CT* with the *segmented brain MRI* directly



Fig. 1. Results for Subject 1. (A) Brain Segmentation: 3D rendering of the *segmented brain MRI*. Note the left frontal porencephaly. (B) MRI-CT Co-registration: The *transformed head CT* produced by the co-registration of the two imaging modalities using the Mango software. (C) ECoG Electrode Segmentation: 3D rendering of the *segmented electrode CT*. (D) Merging: The *segmented electrode CT* merged with the *segmented brain MRI*. The ECoG electrodes were directly placed on the brain cortical surface without any projection.

placed the electrodes on the cortical surface without using projection. Since post-implantation brain deformations are preserved and are similar in both MRI and CT scans, this approach may result in more accurate localization of ECoG electrodes.

A necessary condition for the success of this approach is the successful segmentation of abnormal brains, which is effectively accomplished by the FSL BET tool. Note that segmentation of abnormal brains using the voxel-based morphometry method [3], [4] tends to fail. On the other hand, the FSL BET tool utilizes an evolving deformable model approach, and is therefore more suitable for segmentation of abnormal brains. Furthermore, these results indicate that the evolving deformable model approach is effective even in the presence of extreme brain abnormalities, such as those of Subject 1 (both porencephaly and ECoG electrodes). Note that these extreme abnormalities led to somewhat suboptimal segmentation (e.g. grey matter loss in the pre-frontal lobe and cerebellum), but this did not affect the overall results. In general, most epilepsy patients undergoing ECoG electrode implantation will not have as prominent brain abnormalities other than the ECoG electrode implantation itself (e.g. Subject 2).

The main limitation of the present study is the small sample size and lack of formal validation. Despite the small sample size, this technique was effective even in the case of a subject with extreme brain abnormalities. Given that this is not the norm, it is expected that the method will



Fig. 2. Final imaging processing and labeling of the ECoG grids for Subject 1. The green curve defines the central sulcus. Legend - A: Anterior, P: Posterior, R: Right, L: Left, S: Superior, I: Inferior.



Fig. 3. Final imaging processing and labeling of the ECoG grids for Subject 2. Note the cyctercircosal lesion in the frontal lobe under electrode 29.

generalize to a larger population of subjects undergoing ECoG electrode implantation. Formal validation could be accomplished by comparing the results obtained using this technique to electrode positions derived from high-resolution 3D gradient echo MRI. Since this MRI sequence is not part of standard clinical practice, the current method could not be formally validated in this study.

The main limitation of the current technique is the need for manual steps. In addition, the co-registration step requires a significant understanding of brain anatomy in order properly align relevant anatomical structures. This limitation may be addressed by developing automated procedures for abnormal MRI-CT co-registration. However, this may require novel processing algorithms since current statistical approaches typically do not perform well with abnormal brain images. The current approach results in a loss of image quality, localized to the brain areas under the ECoG grid. This loss of quality is due to the MRI signal artifact caused by the presence of the ECoG electrodes. Nevertheless, important anatomical features are still readily identifiable, such as the central sulcus and the adjacent primary motor and sensory cortices (see Figs. 2 and 3). Finally, if mapping of electrophysiological features onto anatomical space is required, additional processing of the co-registered MRI-CT images is needed to calculate the 3D coordinates of the ECoG electrodes. This, however, can be accomplished by standard image processing techniques, such as finding the centroid of each electrode.

#### V. CONCLUSION

This study demonstrates the feasibility of using postimplantation MRI for ECoG electrode localization. The approach critically depends on the FSL BET tool for proper brain segmentation, which was successfully applied even in the presence of extreme brain abnormalities. Compared to using pre-implantation MRI as the source of brain anatomical data, the current approach circumvents the need for projection of electrode locations, thereby minimizing error in electrode localization. The methodology described here requires only freely distributed software, and can be applied by any researcher who is familiar with brain anatomy and medical imaging processing in ~30 minutes.

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