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Effect of EEG electrode number on epileptic source localization in pediatric patients

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H I G H L I G H T S

- The relationship between source localization and electrode number was investigated in pediatric patients with partial epilepsy.
- Source imaging results were compared with surgical resection and seizure onset zone from intracranial electrodes.
- The source localization is improved when electrode numbers increase, but the absolute improvement is less significant for larger electrode numbers.

A B S T R A C T

Objective: To investigate the relationship between EEG source localization and the number of scalp EEG recording channels.
Methods: 128 EEG channel recordings of 5 pediatric patients with medically intractable partial epilepsy were used to perform source localization of interictal spikes. The results were compared with surgical resection and intracranial recordings. Various electrode configurations were tested and a series of computer simulations based on a realistic head boundary element model were also performed in order to further validate the clinical findings.
Results: The improvement seen in source localization substantially decreases as the number of electrodes increases. This finding was evaluated using the surgical resection, intracranial recordings and computer simulation. It was also shown in the simulation that increasing the electrode numbers could remedy the localization error of deep sources. A plateauing effect was seen in deep and superficial sources with further increasing the electrode number.
Conclusion: The source localization is improved when electrode numbers increase, but the absolute improvement in accuracy decreases with increasing electrode number.
Significance: Increasing the electrode number helps decrease localization error and thus can more ably assist the physician to better plan for surgical procedures.

1. Introduction

Using EEG source imaging to plan for resection has shown promise to aid presurgical planning in medically intractable partial epilepsy patients. Many research groups in the past decades have

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conducted experiments to show the efficacy of using EEG source analysis techniques in the pre-surgical planning for patients diagnosed with focal epilepsy (Ding et al., 2007; Ebersole, 2000; He et al., 1987, 2013; Leijten and Huiskamp, 2008; Lu et al., 2012b, 2014; Michel, 1999; Plummer et al., 2008; Sperli et al., 2006; Wang et al., 2011; Yang et al., 2011). Using the interictal spikes found in the EEG of these patients, such techniques can provide a noninvasive means to assist the physician in localizing the epileptogenic foci. In addition to being noninvasive, EEG recording is a low-cost and fairly available recording module from which a large number of patients can potentially benefit. The availability of powerful personal computers in most clinical environments is another factor that gives the clinician the opportunity to benefit from EEG inverse algorithms. It has been demonstrated in a number of previous studies that such inverse algorithms are capable of localizing the epileptogenic foci with acceptable precision (Fukushima et al., 2012; Ding et al., 2006, 2007; Krings et al., 1998; Lai et al., 2011; Lu et al., 2012a; Michel et al., 2004a; Oikonomou et al., 2012; Wang et al., 2012; Wu et al., 2012; Zhang et al., 2003).

Using a realistic head model for each patient based on their MRI images is another modification that has helped improve the localization of epileptic foci. Using a boundary element method (BEM) model to more accurately model the electric field propagation through brain tissue is one successful step in better modeling the forward solution and has been shown to decrease localization error (Ding et al., 2005; Hämäläinen and Sarvas, 1989; He et al., 1987; Herrendorf et al., 2000; Roth et al., 1997; Wang et al., 2011).

One major concern for EEG recordings was its low number of scalp recordings, which to some degree is lessened by the introduction of high density EEG caps, i.e. nets or caps with 128 electrodes or more (Baillet et al., 2001; He et al., 2011; He and Ding, 2013; Spitzer et al., 1989). Determining the minimum number of electrodes in order to prevent poor performance is an important issue since using too few electrodes translates to undersampling the scalp potential. There have been a number of studies in the past two decades that have tackled this question (Lantz et al., 2003a; Srinivasan et al., 1998; Tucker, 1993). Traditionally, a 3 cm inter-electrode spacing has been suggested (Spitzer et al., 1989; Tucker, 1993), which is generally achieved when about 100 electrodes are used (Gevins, 1993; Michel et al., 2004b; Plummer et al., 2008; Srinivasan et al., 1998). This was experimentally shown to be suitable for a number of applications (Srinivasan et al., 1998; Tucker, 1993).

Although the effect of electrode number on localizing the epileptogenic source has been previously reported in some studies, there is still a need to investigate this matter further in a comprehensive study (Plummer et al., 2008). There have been studies to show the precision of using 128 electrodes when determining the epileptogenic foci (Lantz et al., 2003b; Michel et al., 2004a; Sperli et al., 2006); in addition, recent work has demonstrated the significance of using high density EEG caps versus low density caps in localization error (Wang et al., 2011; Lantz et al., 2003a; Lu et al., 2012a). However, presently there does not exist, to our knowledge, a comprehensive study to clearly delineate the relationship between localization error of interictal spikes and the number of EEG electrodes.

It is also worthy of attention that several work has been reported in the literature based on the recordings from healthy and mostly adult subjects (Junghöfer et al., 2000; McMenamin et al., 2010; Picton et al., 1995, 2000). Nonetheless, as the underlying source and geometry of the head can be very different in pediatric epileptic patients than healthy normal adults, it is reasonable to think that the necessary conditions for an acceptable data recording would be different.

In the present study, the localization error is inspected when the number of electrodes is varied from 32 electrodes to 128 electrodes. Furthermore, the localization error (which is usually calculated based on resection volume) is also calculated by comparing the maxima of the reconstructed solution with *electrocorticogram* (ECoG) electrodes that were marked as seizure onset zone (SOZ) electrodes by the epileptologists. ECoG recording is considered the gold standard for identifying SOZ foci (Engel, 1987); thus, including ECoG data to verify source localization results is another important feature of this study.

2. Methods

2.1. Patients and data acquisition

Five pediatric patients with medically intractable partial epilepsy were studied using a protocol approved by the Institutional Review Boards of the University of Minnesota and University of Alabama at Birmingham. The patients were all under 16 years of age. The patients were selected based on the following criteria: (1) interictal spikes were recorded in their high density preoperative EEG recordings, (2) patients underwent surgical resection after presurgical workup, (3) patients were seizure free after operation, and (4) high resolution MRI images were taken preceding and following the operation. The surgical resection was used to evaluate the source localization accuracy and was not used to obtain the inverse solution. The lesion sizes, obtained from post-operative MRI images, are 9.5, 45.8, 2.1, 15.1 and 18.9 cm^3 in patients 1–5, respectively. The clinical information of these patients is summarized in Table 1.

The location of the epileptogenic foci was specified for each patient by neurologists using high resolution MRI, long term video-EEG recordings prior to surgery, ictal intracranial EEG and SPECT when available. The patients underwent surgery and had the epileptogenic foci resected. All patients were seizure free during a one year follow up with the exception of one patient (patient 5) who underwent a second surgery and was seizure free during a two year follow up.

During the long term monitoring prior to surgery, 128 channel scalp EEG recordings with 250 or 500 Hz sampling rate were collected. A band pass filter of 1–30 Hz was used to filter the linear trend and high frequency noise (Lu et al., 2012a). The MR images (voxel size: $0.86 \times 0.86 \times 3$ or $0.86 \times 0.86 \times 1.5\ mm^3$) were obtained from a 1.5T GE MRI scanner (General Electric Medical Systems, Milwaukee, WI). Electrode location for each patient was not available (as a digitized file); thus, in order to find the electrode location for each patient, a generic electrode location file that was provided by the EEG system vendor (Electrical Geodesics Inc., Eugene, OR) was used. The sensors were projected to each patient's head using the patients' MRI images. In order to better fit the electrodes, landmarks such as ear location, nasion and inion have been taken into consideration when projecting the electrodes onto the patient's head. This will decrease the mismatch between the true electrode location and the ones used in analysis. In order to study different electrode configurations, i.e. electrode numbers, the electrodes were selected in a manner to uniformly cover the whole head, in an attempt to be as close as possible to the original/modified 10–20 system.

2.2. Data analysis

The pre-operative scalp EEG recordings were reviewed and the interictal events were identified. In order to minimize the possibility of including rare events, i.e. non-epileptic events, all scalp potential maps were reviewed and the spikes pertaining to the dominant spatial map were selected for analysis. Priority was