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Cortical Potential Imaging of Somatosensory Evoked Potentials by Means of the Boundary Element Method in Pediatric Epilepsy Patients

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Abstract

The aim of the present study was to assess the feasibility of identifying the primary hand sensory area and central sulcus in pediatric patients using the cortical potential imaging (CPI) method from the scalp recorded somatosensory evoked potentials (SEPs). The CPI method was used to reconstruct the cortical potential distribution from the scalp potentials with the boundary element (3-layer: scalp, skull and brain) head model based on MR images of individual subjects. The cortical potentials estimated from the pre-operative scalp SEPs of four pediatric patients, were compared with the post-op subdural SEP recordings made in the same subjects. Estimated and directly recorded cortical SEP maps showed comparable spatial patterns on the cortical surface in four patients (spatial correlation coefficient > 0.7 in the SEP spikes). For two of four patients, the estimated waveforms correlated significantly to the waveforms obtained by direct cortical recordings. The present results demonstrated the feasibility of the cortical potential imaging approach in noninvasive imaging spatial distribution and temporal waveforms of cortical potentials for pediatric patients. These also suggest that the CPI method may provide a promising means of estimating the cortical potential and noninvasive localizing the central sulcus to aid surgical planning for pediatric patients.

Keywords

High-resolution EEG; cortical potential imaging; SEP; central sulcus; cortical potential waveform

1 Introduction

Electroencephalography (EEG) is widely used for monitoring brain electrical activity. The conventional EEG has millisecond temporal resolution and is an economic and easy-to-use diagnostic modality. However, the low spatial resolution of the conventional EEG limits its use for imaging spatially distributed brain electrical activity. Efforts have been made to solve the so-called EEG inverse problem to substantially improve the spatial resolution of EEG (He et al., 1987; Michel et al, 2004; Nunez & Srinivasan, 2005; He & Lian, 2005). Among them, of interest is the development of *cortical potential imaging* (CPI) techniques, in which the cortical potential is estimated noninvasively from the scalp potentials to improve spatial resolution of scalp EEG (Sidman et al, 1990; Srebro et al., 1993; Gevins et

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al., 1994; Nunez et al, 1994; He et al., 1996, 1999, 2001, 2002; Babiloni et al., 1997; Wang & He, 1998; Zhang et al., 2003; Zhang et al., 2006a).

Among the several CPI techniques, the finite element method (FEM) based CPI (Gevins et al., 1994) and the boundary element method (BEM) based CPI (He et al., 1999) are the only two algorithms which were evaluated using the subdural ECoG recordings in few adult neurosurgical patients. Gevins et al. (1994) compared the spatial maps of noninvasive cortical potentials estimated using their FEM based CPI technique, with the subdural electrocorticograms (ECoGs) in two patients. He et al. (2002) evaluated quantitatively their BEM-based CPI results with the subdural ECoG recordings in three neurosurgical patients. To date, no reports have been made with regard to the applications of the CPI to pediatric subjects as validated by the subdural recordings. Furthermore, no attempt has been made to estimate the temporal waveforms of ECoGs from the scalp EEG recordings by using the CPI approach.

In the present study, we assessed the ability of the BEM-based CPI method to image the cortical potential distributions in four pediatric patients. The recorded and estimated cortical waveforms obtained from clinical pre-operative scalp EEG recordings and post-operative direct cortical mappings were correlated in two pediatric patients studied. Both the recorded and estimated cortical potentials were successfully used to determine the position of the central sulcus.

2 Materials and Methods

2.1 Cortical potential imaging

The CPI method developed by He and co-workers (1999) was used in the present study. In brief, since brain electrical sources exist only inside the brain, Green's second identity is used to describe the volume between the scalp and the skull and the volume between the skull and the brain, separately. After some mathematical manipulations, the cortical potential $\mathbf{V}_c$ can be directly connected with the scalp potential $\mathbf{V}_s$ as

$$\mathbf{V}_s = \mathbf{G}_{sc} \mathbf{V}_c, \quad (1)$$

where $\mathbf{G}_{sc}$ is a transfer matrix from the cortical potentials to the scalp potentials, which can be constructed by the boundary element (BE) head model. However, because the number of electrodes is limited in the real measurement, the measured scalp potential vector $\tilde{\mathbf{V}}_s$ is usually a subset of the potential vector $\mathbf{V}_s$. Therefore, $\tilde{\mathbf{V}}_s$ can be related to the cortical potential vector $\mathbf{V}_c$ by the sub-relation as:

$$\tilde{\mathbf{V}}_s = \mathbf{T} \mathbf{V}_c, \quad (2)$$

where $\mathbf{T}$ is the sub-matrix of $\mathbf{G}_{sc}$.

The inverse solution of CPI is to estimate the solution of the unknown cortical potential vector $\mathbf{V}_c$ from the measured scalp potential vector $\tilde{\mathbf{V}}_s$. In this inverse process, an ill-posed nature of the inverse problem must be considered. In the present study, the zero-order Tikhonov regularization is applied (Tikhonov & Arsenin, 1977):

$$\mathbf{V}_c = (\mathbf{T}^T \mathbf{T} + \lambda \mathbf{I})^{-1} \mathbf{T}^T \tilde{\mathbf{V}}_s, \quad (3)$$

where λ is the regularization parameter, which is used to suppress the influence of noise. In the present study, the determination of the regularization parameter λ was calculated by using an L-curve approach in Hanson's regularization tools (Version 3.2 for Matlab 6.0, <http://www2.imm.dtu.dk/~pch/Regutools/>), in which the optimal λ is automatically chosen at corner point of the L-curve (using `L_curve.m` in the Hanson's regularization tools) (Hansen, 1990, 1994).

2.2 Pediatric Patients

2.2.1 Subjects—Eight neurosurgical pediatric epilepsy patients were studied with a protocol approved by the Institutional Review Boards of the University of Chicago and the University of Minnesota. All data of eight pediatric patients including the structural (MR) images, computerized tomography (CT) images, and the direct cortical and scalp SEP recordings with scalp electrode locations were collected in the Pediatric Epilepsy Center at The University of Chicago Children's Hospital. Four of eight subjects were rejected due to poor scalp SEPs. The data from four pediatric patients were analyzed and reported here (4 female; averaged age: 10.4 years old). The N20 and P30 components were used for localizing the central sulcus in the previous studies (He et al., 2002; Waberski et al., 2002; Bai et al., 2007). So both N20 and P30 components are used in the present study.

2.2.2 SEP Recordings—The scalp and direct cortical SEP recordings of eight neurosurgical pediatric patients were obtained in a relaxed and awake state without the use of sedatives. The scalp SEP recordings were made several days before the implantation of the subdural electrodes. Both the scalp and direct cortical SEP recordings of the pediatric patients were elicited by electrical stimulation of the median nerve at the wrist. The stimuli were 0.2-ms-duration electrical pulses delivered at 5.7 Hz at motor threshold. Five replications of 500 stimuli were averaged. Using a commercial signal acquisition system (Neuroscan Labs, El Paso, TX), 24-channel scalp EEG referenced to Cz was amplified with gain of 5000 (sampling rate) and band-pass filtered from 1 Hz to 1 kHz.

The direct cortical SEP data were recorded from a 4×8 rectangular (patient #1 and #2) or 8×8 square (patient #3 and #4) subdural electrode grid with an interelectrode distance of 1 cm. The subdural electrode grids were placed directly on the surface of the brain of pediatric patients as part of their diagnostic evaluation for the surgery. In the measurement, each channel of direct cortical SEP recordings referenced to the contralateral mastoid was also band-pass filtered from 1 Hz to 1 kHz, but a gain of 1000 Hz (sampling rate) was used (Neuroscan Labs, El Paso, TX).

2.2.3 MR images and Boundary element modeling—The MR images of the pediatric patients were obtained from each pediatric subject with a Siemens 1.5 Tesla scanner using T1-weighted images. Later, the BE head models including three compartments (skin, skull and brain) were constructed from these MR images of pediatric patients by Curry 5.0™ (NeuroScan, 2004), in which three compartments of BE head models were structured by approximately 3000 nodes. At the same time the cortex surfaces of two pediatric patients (patient #2 and #3) were also constructed by over 8000 nodes. Due to the lower spatial resolution of structure MRI (scanned slice number), the cortex surfaces of another two patients (patient #1 and #4) were not successfully created. The inter-node distances of the brain, skull, skin and cortex layers were 7, 9, 10 and 3 mm approximately. Number of nodes (N) and number of triangles (T) in three layers (scalp, skull and brain) of BE head models for four pediatric patients were shown in Table 1. The conductivities of the skin, skull and brain were assumed to be 0.33, 0.0165 and 0.33 S/m respectively (Oostendorp et al., 2000; Lai et al., 2005; Zhang et al., 2006b). This BE head modeling

approach has been widely used in the source localization and current density reconstruction with EEG/MEG (He et al., 2005; Fuchs et al., 2001).

2.2.4 Registration of scalp electrodes—For all pediatric patients, while the scalp SEP recordings were obtained, all 24 electrode locations and 5 landmark points (nasion, preauricular left, preauricular right,inion, and vertex) were also determined by radiofrequency localizer (Polhemus Fastrak, VT). At the same time approximately one hundred and fifty points on the scalp were digitized along with all electrode locations and landmark points, which can provide a patient-specific coordinate reference to register the electrode locations with the MR images. Using Curry 5.0™, seven landmark points (nasion, preauricular left, preauricular right,inion, vertex, anterior commissure and posterior commissure) were determined manually in the MR images. After the electrode location recording with 24 electrode and 5 landmark points were input the Curry 5.0™, the Curry 5.0™ can co-register automatically the MR images with the electrode location recording based on first five landmark points (Zhang et al., 2006a).

2.2.5 Registration of subdural electrodes—The MR and postoperative CT images were co-registered using 5 landmark points (nasion, preauricular left, preauricular right,inion, and vertex) in Curry 5.0™. Later, the subdural electrode grids of pediatric patients were segmented using Curry 5.0™ from the postoperative CT images. Because the subdural electrode grids were the 4×8 rectangular or 8×8 square shape, only four corner electrodes were needed to characterize their locations on the brain surface. When four corner electrodes were determined from segmentation by Curry 5.0™, the other subdural electrode locations of the grid were generated by the surface path fitting algorithm of Curry 5.0™ with known subdural electrode arrangement (Zhang et al., 2006a).

2.2.6 Identification of the central sulcus based on direct subdural recordings—According to the features of SEPs published in the literature (He et al., 2002; Waberski et al., 2002; Towle et al., 2003), N20 and P30 components have been used for localizing the central sulcus. For example, in the N20 component, the positivity of the dipolar pattern corresponds to the motor area (the front of the central sulcus), and the negativity corresponds to the somatosensory area (behind the central sulcus). Comparing the zero-potential line separating the negativity and positivity with the cortex's sulcus, the central sulcus, motor and sensory areas can be identified accordingly. In addition, Yousry and co-worker (1997) suggested that the segment of the precentral gyrus that contained motor hand function was a knob-like structure, which is shaped like an omega or epsilon in the axial plane and like a hook in the sagittal plane. In the present study, the primary motor hand area and the primary sensory hand area, and the central sulcus were determined by the direct subdural potential maps and gyral anatomy.

2.3 Analysis Protocol

The protocol of the present study is illustrated in Fig. 1. First, the scalp electrodes were located on the MR images by registration of scalp electrodes. The realistic geometry head model (the BE head model) was constructed by the MR images of pediatric patients using Curry 5.0™. Second, the subdural electrodes of pediatric patients were registered on the BE model by the MR and postoperative CT images. Third, the estimated cortical potentials were calculated by the present CPI method from the measured scalp potentials. Last, the ECoG recordings were used to assess the estimated cortical potentials including the cortical potential maps and temporal waveform of each channel.

2.4 Evaluation Protocol

The accuracy of the inverse solution of the present CPI method were evaluated by the spatial correlation coefficient (CC_{sp}) and temporal correlation coefficient (CC_{temp}) to only 2 decimal places separately. The spatial correlation coefficient (CC_{sp}) was used to evaluate between the estimated and measured cortical potential spatial map of each time point as

$$CC_{sp}(t) = \frac{(\tilde{\mathbf{V}}_c(t) - \bar{\tilde{\mathbf{V}}}_c(t)) \cdot (\mathbf{V}_c(t) - \bar{\mathbf{V}}_c(t))}{\|\tilde{\mathbf{V}}_c(t) - \bar{\tilde{\mathbf{V}}}_c(t)\| \|\mathbf{V}_c(t) - \bar{\mathbf{V}}_c(t)\|}, \quad (4)$$

where $\tilde{\mathbf{V}}_c$ and $\mathbf{V}_c$ are the measured and estimated cortical potential vectors in t -th instant time point, and $\bar{\tilde{\mathbf{V}}}_c$ and $\bar{\mathbf{V}}_c$ are means of $\tilde{\mathbf{V}}_c$ and $\mathbf{V}_c$ respectively. The temporal correlation coefficient (CC_{temp}) was to compare waveforms of each channel between the estimated and measured cortical potential recordings, which was defined as

$$CC_i^{temp} = \frac{(\tilde{\mathbf{V}}_c^i - \bar{\tilde{\mathbf{V}}}_c^i) \cdot (\mathbf{V}_c^i - \bar{\mathbf{V}}_c^i)}{\|\tilde{\mathbf{V}}_c^i - \bar{\tilde{\mathbf{V}}}_c^i\| \|\mathbf{V}_c^i - \bar{\mathbf{V}}_c^i\|}, \quad (5)$$

where $\tilde{\mathbf{V}}_c^i$ and $\mathbf{V}_c^i$ are the measured and estimated cortical potential vectors of i -th channel during a time slice (from 5ms to 50ms after the onset of median nerve stimuli), and $\bar{\tilde{\mathbf{V}}}_c^i$ and $\bar{\mathbf{V}}_c^i$ are means of $\tilde{\mathbf{V}}_c^i$ and $\mathbf{V}_c^i$ respectively.

3 Results

The cortical potential maps estimated from the scalp SEPs in four subjects show comparable spatial distributions as compared with the direct subdural ECoG maps during the same somatosensory protocol.

The results from patient #1 are shown in Fig. 2. Fig. 2 (a, b) shows the recorded scalp potential and the direct cortical potential maps at four time instants approximately 19 ms after the onset of right median nerve stimuli. A positivity / negativity dipolar pattern was observed over the left side of the scalp, although the positive region was located on the anterior scalp and the negative region was stronger than the positive region. The direct subdural potential maps in Fig. 2 (b) gave the higher spatial resolution than the scalp potential maps, in which the positivity / negativity dipolar pattern was observed clearly in the rectangular region covered by the subdural electrodes. The estimated cortical potential maps are shown in Fig. 2 (c), and the CC_{sp} is listed at the bottom of Fig. 2 (c). Comparing maps of Figs. 2 (b, c), the negative region of both estimated and direct recorded cortical maps were located on the same position of the grid surface; but the positive region can not be identified from the estimated cortical potential maps (Fig. 2 (c)). However, averaged over ten time instants, i.e., from 18.0 ms to 19.8 ms with 0.2 ms interval, the mean CC_{sp} of 0.808 with standard deviation of 0.032 was obtained, which suggests that the cortical potential maps were well reconstructed from the noninvasive scalp SEPs during the epoch. Similarly, Figs. 2 (d, e, f) show the measured scalp potential, direct subdural cortical potential, and estimated cortical potential maps in patient #1, respectively, at four time instants

approximately 26 ms after the onset of right median nerve stimuli. Different from N/P19, an opposite polarity in the spatial patterns of N/P26 was observed. Here, the positive region from the estimated cortical maps was also close to direct subdural cortical maps. And the negative area was not identified from the same position of the estimated cortical maps. The mean of CC_{sp} was 0.809 with a standard derivation of 0.025, averaged over ten time instants, i.e., from 25.0 ms to 25.8 ms with 0.2 ms interval, which suggests that the cortical potential maps can be reasonably estimated from noninvasive scalp SEPs.

Results from pediatric patient #2 are shown in Fig. 3. Figs. 3 (a, b, c, d) show the measured scalp potential, direct recorded grid potential, estimated grid potential and entire estimated potential with the cortex surface for patient #2, respectively, at four time instants approximately 25 ms after the onset of left median nerve stimuli. The dash curves of Figs. 3 (a, b, c, d) express the central sulcus of patient #2. Comparing Fig. 3 (b) with Fig. 3(c), the positive region of both estimated and direct recorded potential maps was located on the same position of the grid surface. Averaged over ten time instants, i.e., from 24.0 ms to 25.8 ms with 0.2 ms interval, the mean CC_{sp} of 0.76 with a standard deviation of 0.027 was obtained, which suggests the consistency between the estimated and measured cortical potentials maps.

Figs. 4 (a, b, c) show the measured scalp potential mappings, the direct recorded grid potentials and the estimated grid potentials for patient #3, respectively, at four time instants approximately 25 ms after the onset of right median nerve stimuli. The positivity / negativity pattern was observed clearly in the Fig. 4 (b). According to the features of SEPs published in the literature (He et al. 2002; Waberski et al., 2002; Towle et al., 2003; Barba et al., 2004), the negativity and positive dipolar pattern corresponded to the motor area (the front of the central sulcus) and somatosensory area (behind the central sulcus). The dash curves of Figs. 4 (a, b, c) express the central sulcus of patient #3. Comparing Fig. 4 (b) with (c), the distance between the extrema of the positive / negative regions was slightly larger in the estimated cortical potential maps as compared with that in the direct recorded maps. The positive region of both the estimated and recorded maps was located on the same position. The mean of CC_{sp} was 0.745 with a standard derivation of 0.03, averaged over ten time instants, i.e., from 24.4 ms to 26.2 ms with 0.2 ms interval. Fig. 4 indicates that the spatial features in the post-op subdural ECoG recordings were well reconstructed from the pre-op scalp SEP recordings, and that the central sulcus in the patient was well identified from the CPI results. Consistently, Figs. 5 (a, b, c, d) showed the measured scalp potential, direct recorded potential, estimated cortical potential and entire estimated potential maps for pediatric patient #4, respectively, at four time instants approximately 17 ms after the onset of left median nerve stimuli. The negative regions of both estimated and direct recorded cortical mappings were located on the same position of the grid surface. The positive region shown in Fig. 5 (b) was generated by the noise or other activity, which did not express the motor area (the front of the central sulcus). Averaged over ten time instants, e.g., from 16.2 ms to 17.4 ms with 0.2 ms interval, the mean CC_{sp} of 0.703 with a standard deviation of 0.031 was achieved. Therefore, the results of patient #4 also indicated that most of brain source activity was reconstructed in the estimated cortical maps.

Figs. 6 (I, II) show the estimated and measured waveforms (right view) and CC_{temp} of each channel, from 5 ms to 50 ms after the onset of left median nerve stimuli for patient #2. In Figs. 6 (I, II), the estimated waveforms of most channels were quite similar to the direct cortical recording. However, deviations were also observed in the channels (1f, 1g, 1h, 2g, 4g, 4h) between the estimated and measured waveforms. Figs. 7 (I, II) show the estimated and measured waveforms (left view) and CC_{temp} of each channel, from 5 ms to 50 ms after the onset of right median nerve stimuli for patient #3. According to the features of SEPs published in the literature (He et al. 2002; Waberski et al., 2002; Towle et al., 2003; Barba et

al., 2004), the typical waveforms of cortical SEP recording in the motor area include both the first positive (P20) and later negative (N30) peaks, and the typical waveforms in the sensory area consisted of the first negative (N20) and later positive (P30) peaks. In Fig. 7 (I), the estimated waveforms corresponding to motor and sensory areas were located on approximately 3b and 3g separately. The recorded waveforms corresponding to motor and sensory areas were located on approximately 3e and 3f. And the SEP activity was not observed from waveforms of (5-8, a-h). In Fig. 7 (II), CC_{temp} of (2-4, a-d) and (2-4, f-h) were higher than 0.7. These results indicate that the estimated and recorded waveforms of these channels were close. In particular, the estimated waveforms of 2f, 2g, 3c, 3f and 3g were more similar to the recorded waveforms than others. Since the spatial resolution of estimated results was lower than the direct recording due to the finite scalp electrode number and the inverse estimation procedure, the cortical potential waveforms were not well reconstructed at 2e, 3e and 4e. The same temporal analysis also was performed in patient #1 and #4. Due to the signal noise generated by the movements and limited number electrodes, cortical potential waveforms were not successfully reconstructed from the scalp potentials.

4 Discussion

The Electrocorticography (ECoG) has been widely used in the clinical diagnosis and neurophysiology research (Engel et al., 1981; Modayur et al., 1997; Ochi et al., 2000; Graimann et al., 2002; Hansson et al., 2003; kaňovský, 2003; Karatas et al., 2004; Debatisse et al., 2005; Kinoshita et al., 2005; Kumabe et al., 2005). Specifically, direct cortical stimulation has been accepted as a “gold standard” to determine the motor and sensory areas in awake humans. However, the invasiveness, risk of morbidity, limited availability, and high cost of this technique limited its routine clinical use (Huppertz et al., 2001).

The cortical potential imaging approach has been pursued by several groups in an attempt to noninvasively estimate the cortical potentials from the scalp EEG recordings (Srebro et al., 1993; Gevins et al., 1994; He et al., 1996, 1999, 2001, 2002; Babiloni et al., 1997; Wang & He, 1998; Zhang et al., 2003; Zhang et al., 2006a). The technique developed by He and co-workers (1999) showed promise in computer simulations and experimental evaluation in few adult patients (He et al., 2002).

In the present study, we evaluated the performance of the CPI method with somatosensory evoked potentials (SEPs) including the scalp and direct cortical (ECoG) recordings elicited by the electrical stimulation of the median nerve at the wrist from four neurosurgical pediatric patients. Comparing pediatric patients with adult patients, more complex and difficult conditions on clinical measurement need to be faced such as the increase of signal noise and the decrease of number of scalp electrodes.

Our main results are as follows. First, as displayed in Figs. 2-7, we can clearly observed that the main activity of both estimated and direct recorded cortical mappings located on the same position of the grid surface. Results are in accordance with those reported in the previous literature (He et al. 2002; Towle et al., 2003). Second, the negativity / positivity pattern of estimated cortical mapping with 24 channels was not as good as the adult patients' results with 32 channels. In Fig. 4, the positive region of estimated cortical potential was the same as the direct cortical mapping. The negative region of estimated cortical potential was more anterior than the direct cortical map. Comparing the cortical potential mappings of pediatric patient (24 channels) and results of adult patients (32 channels) shown in He et al. (2002), the positive / negative pattern of the estimated cortical potential map (He et al., 2002) was more clear for the adult patients than the pediatric patients. Third, the cortical potential waveform reconstructions were successively implemented in two pediatric patients, as shown in Fig. 6 and 7. Although estimated waveforms of some channels (1f-1h

in Fig. 6 and 3b in Fig. 7) are not close to the recorded signals, the estimated waveforms in the most of channels excellently match the waveforms ($CC_{temp} > 0.5$) obtained from the direct subdural recordings.

On the basis of our results in the present and previous studies (He et al., 1999; 2002), we have the following remarks on the application of the CPI approach: 1) The CPI method can improve significantly the spatial resolution of scalp EEG recording and successively reconstruct the cortical potential maps for the shallow source (the source is very close to the cortical surface) for both adult and pediatric patients. 2) The electrode number is extremely important to improve the spatial resolution of the reconstructed cortical potential map, particularly for identifying the central sulcus by using scalp SEP recordings in the clinical application. We suggest that the scalp electrode number is larger than 32 for the clinical application. The detailed simulation study for various number of scalp electrodes has been reported in our previous study (He et al., 2002). 3) The source imaging approaches involved in the cortical current density reconstruction and dipole source localization have appeared to be promising for the analysis of epileptic EEG data. Recently several studies have reported the significant improvement of the source localization accuracy (Ding and He, 2008; Plummer et al., 2008; Bai et al., 2007; Ou et al., 2009). But in the diagnosis and clinical treatment of epilepsy, the ECoG nowadays plays a primary role to identify the location of seizure zone and important functional areas such as motor, sensor and cognitive abilities. The neurologists and neurosurgeons have accumulated numerous experiences of the ECoG patterns associated with a wide variety of paroxysmal phenomena of seizures and electrographic phenomena of important brain functions. Performing the CPI method simultaneously with other source image approaches can provide more useful information to neurologists for clinical application. Hence, the CPI approach is also a helpful and useful tool for the other EEG source imaging approaches (Ding and He, 2008).

Our study has some limitations. For the EEG recordings in children, Fifer et al. 2004 already showed that at least 64 electrodes may be put on the head of the normal infant. Thus, using EEG data with more electrodes to estimate the feasibility of our CPI approach is desirable. Another limitation of this study is that we analyzed only 4 patients in cortical potential mapping and 2 patients in temporal potential dynamic waveforms. A more valid feasibility analysis might need to include more patients. Third, small children often have difficulty staying still for the length of time needed to do entire SEP. Due to this problem, both N20 and P30 components can be obtained from 2 of 8 patients. How to minimize this problem in pediatric patients need to be considered in the future study.

In summary, the present study examined the feasibility of imaging cortical potentials elicited by somatosensory stimulation in pediatric subjects. The results we have obtained suggest that CPI can be used to estimate the general pattern of cortical potentials at N20/P30 latencies with good accuracy as assessed by comparing to directly recorded cortical potentials under the same stimulation in the same pediatric subjects.

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Fig. 1. Schematic diagram of the procedures of cortical potential imaging with the real EEG and ECoG recordings of pediatric patients; (1) and (2) express the registration of scalp electrodes and registration of subdural electrodes respectively.

Fig. 2.

(a), (b) and (c) show results at four time instants approximately 19 ms after the onset of right median nerve stimuli for pediatric patient #1; (d), (e) and (f) show results at four time instants around 26 ms after the onset of right median stimuli for patient #1. (a) and (d) are the recorded scalp potential maps; (b) and (e) the direct recorded subdural grid potential maps; and (c) and (f) the estimated subdural grid potential maps. The latency and CC_{sp} value between the estimated and the recorded subdural grid potential maps for each time instant are listed at the bottom.

Fig. 3. Scalp EEG and cortical potentials at four time instants approximately 25 ms after the onset of left median nerve stimuli for pediatric patient #2. (a) the recorded scalp potential maps; (b) the direct recorded subdural grid potential maps; (c) the estimated subdural grid potential maps. The latency and CC_{sp} value between the estimated and the recorded subdural grid potential maps for each time instant are listed at the bottom. The black dotted curve illustrates the central sulcus.

Fig. 4. Scalp EEG and cortical potentials at four time instant around 25 ms after the onset of right median nerve stimuli for pediatric patient #3. (a) the recorded scalp potential maps; (b) the direct recorded subdural grid potential maps; (c) the estimated subdural grid potential maps; (d) the entire estimated subdural potentials. The latency and CC_{sp} value between the estimated and the recorded subdural grid potential maps for each time instant are listed at the bottom. The black dotted curve illustrates the central sulcus.

Fig. 5. Scalp EEG and cortical potentials at four time instant approximately 17 ms after the onset of left median nerve stimuli for pediatric patient #4. (a) the recorded scalp potential maps; (b) the direct recorded subdural grid potential maps; (c) the estimated subdural grid potential maps; (d) the entire estimated subdural potentials. The latency and CC_{sp} value between the estimated and the recorded subdural grid potential maps for each time instant are listed at the bottom.

Fig. 6.

Waveforms (over the right hemisphere) from 5 ms to 50 ms after the onset of left median nerve stimuli for pediatric patient #2. A 4×8 rectangular electrode grid with interelectrode distance of 1 cm was used to record the ECoGs. Both EEG and ECoG were sampled at 5000 samples per second; (I) waveforms of the recorded ECoGs (solid lines) and the estimated subdural grid potentials (dashed lines); (II) distribution of the CC_{temp} of all channels, where CC_{temp} is the correlation coefficient between the estimated and the recorded subdural grid potential waveforms for each channel. Note that for most channels the temporal waveforms of ECoG were well estimated from the scalp EEG.

Fig. 7.

Waveforms (over the left hemisphere) from 5 ms to 50 ms after the onset of right median nerve stimuli for pediatric patient #3. A 8×8 rectangular electrode grid with interelectrode distance of 1 cm was used to record the ECoGs. Both EEG and ECoG were sampled at 5000 samples per second. (I) waveforms of the recorded ECoGs (solid lines) and the estimated subdural grid potentials (dashed lines); (II) distribution of the CC_{temp} of all channels, where CC_{temp} is the correlation coefficient between the estimated and the recorded subdural grid potential waveforms for each channel. Note that for most channels the temporal waveforms of ECoG were well estimated from the scalp EEG.

Table 1

Number of nodes (N) and number of triangles (T) in three layers (scalp, skull and cortical surfaces) of the BE head models for four pediatric patients

	Scalp		Skull		Cortical	
	N	T	N	T	N	T
Patient 1	742	1480	992	1980	1365	2726
Patient 2	1190	2376	1192	2380	1494	2984
Patient 3	902	1800	910	1816	1268	2532
Patient 4	674	1344	870	1736	1177	2350