

The Relationship between Conductivity Uncertainties and EEG Source Localization Accuracy

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Abstract. The aim of the present study was to investigate the relationship between the brain-to-skull conductivity ratio (BSCR) and EEG source localization accuracy by means of a simulation protocol. In the present study, we evaluated seven BSCRs, which are commonly used in the literature. Simulations were conducted for both dipolar and distributed source models. Source reconstruction was performed using dipole estimation and standardized low resolution brain electromagnetic tomography (sLORETA) for each BSCR. The estimated source activities were compared with the simulated dipolar points or the centers of the distributed source volumes. BSCRs were found to impact the localization outcome significantly for BSCRs that were greatly different from the values used in the forward model.

Keywords: EEG, Conductivity, Source Imaging, Source localization

1. Introduction

The electroencephalography (EEG) measures scalp electrical potentials propagated from neuronal activity within the brain through the head volume conductor. These signals have been widely applied in neuroscience research [Michel et al, 2004 and He et al, 2005] and used in clinical applications [Ding et al, 2007, Leijten et al, 2008]. Many efforts have been made to solve the so-called EEG inverse problem, which aims at reconstructing brain electrical activity from scalp EEG measurements. In majority of the EEG source localization methods, a piecewise homogenous head model is used to represent the physical properties of the head volume conductor. This model usually consists of three compartments (brain, skull and scalp), which are segmented from MR images. The conductivities of different tissues play an important role in determining the relationship between the recorded scalp potentials and neuronal currents within the brain. In these head models, it is usually assumed that the scalp has the same conductivity as the brain while the skull has a much lower conductivity. A number of efforts have been made to estimate the brain-to-skull conductivity ratio (BSCR) and large range of this value has been reported [Oostendorp et al, 2000, Hoekema et al, 2003, Lai et al, 2005, Zhang et al, 2006]. Although several simulation studies have been carried out [Awada et al, 1998 and Huiskamp et al, 1999], to our knowledge, it is yet to conclude the debate over the role of BSCR in source localization accuracy. In this paper we report a computer simulation study to examine quantitatively the relationship between BSCR and EEG source localization.

2. Methods

In order to evaluate the relationship between conductivity uncertainties and EEG source localization accuracy, we conducted two computer simulation studies to access effects of seven previously reported BSCRs values: 8, 15, 20, 25, 40, 80, and 120. For head modeling, we used the realistic geometry of Colin's brain [Holmes et al., 1998] with three compartments (scalp, skull, and brain) by the boundary element method (BEM) [He et al, 1987, Hamalainen et al, 1989]. The three compartments were segmented from MR images of Colin brain model using CURRY6 software (Compumedics, Charlotte, NC). The conductivities of the scalp and the brain were assumed to be 0.33 S/m. The conductivity of the skull can be determined by the BSCRs mentioned above. Seven BEM models were built with the corresponding BSCRs.

2.1. 1000 Dipolar Sources Simulations

1000 dipolar sources were randomized in both direction and location as sources in the forward model. Locations of the dipole sources were confined within the realistic cortex volume segmented from MR images of Colin brain. In the forward model, BSCR was assigned to be 20 [Zhang et al, 2006]. The surface potential at electrodes of a 10-10 montage with 76 electrodes was computed. Noise

was added to simulate realistic EEG signals with signal to noise ratio (SNR) =10. These surface potentials were used as EEG input for subsequent inverse analysis. The conductivities of the scalp and the brain were assumed to be 0.33 S/m for both forward and inverse computation. The red arrow in Fig 1 (a) illustrates one dipolar source.

Two well adopted source localization methods implemented in CURRY6, dipole estimation and sLORETA, were used for inverse source reconstruction. For dipole estimation, the source was assumed to be a dipolar point, illustrated by the green arrow in Fig 1 (a). And the localization error was calculated as the distance between coordinates of the estimated dipole to the simulated source dipole. As sLORETA gives an estimation of three-dimensional current density distribution, the localization error was calculated as the distance between the location of the maximal current density points estimated and the simulated dipole. The solution space was defined as 3D grid inside the brain.

2.2. 200 Distributed Sources Simulations

200 distributed sources were randomized as sources in the forward model. Similarly to the dipolar source simulation, locations of the centers of the simulated current distribution were confined within the cortex volume. In the forward model, BSCR was assigned to be 20 [Zhang et al, 2006]. The surface potentials calculated in the forward model with added noise were used as EEG input for subsequent inverse analysis. The conductivities of the scalp and the brain were assumed to be 0.33 S/m for both forward and inverse computation. The warm colored crosses signify the strength of the simulated current density, which follows a Gaussian distribution shown in Fig. 1 (b). The red cross at the center represents the peak of the simulated current density.

Both dipole estimation and sLORETA were used for localization as displayed. The green arrow represents the estimated dipole using dipole estimation. Cool colored crosses illustrate the estimated current distribution using sLORETA. Localization error was determined as the distance from the estimated dipole source to the peak of the simulated current density, as in the dipole estimation method; or the distance between the locations with maximum strength of the estimated current density distribution to the peak of the simulated current density distribution as in the sLORETA method.

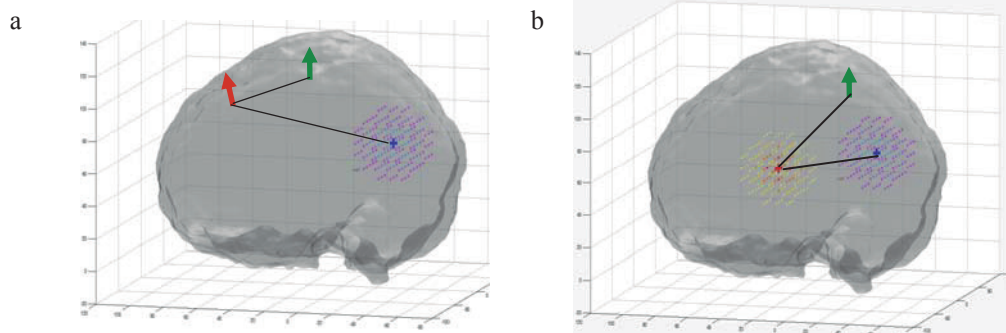


Figure 1. (a) Illustration of dipolar source simulation and localization. Red arrow: simulated dipolar source. Green arrow: estimated source using dipole estimation method. Cool colored crosses: estimated current distribution from sLORETA. Blue cross: peak of the estimated current density distribution. (b) Illustration of distributed source simulation. Warm colored crosses: simulated current density distribution that follows a Gaussian distribution. Red cross: peak of the simulated current density distribution. Green arrow: estimated source using dipole estimation method. Cool colored crosses: estimated current distribution from sLORETA. Blue cross: peak of the estimated current density distribution.

2.3. Statistical testing

In order to compare source localization results of different BSCRs, Tukey's pairwise comparison test was performed for the localization results. The means of the localization errors resulted from each BSCR were computed and arranged in an ascending order. Means that were not statistically different were marked with an underline. The significance level was set at $p < 0.05$.

3. Results

3.1. 1000 Dipolar sources Simulation

Simulation results for 1000 dipolar cortical sources with different inverse BSCR values are shown in Fig. 2 (a). The dipole estimation method shows a consistently higher localization error comparing to

sLORETA. The mean localization error for dipole estimation method ranges between 2.7 mm for BSCR = 20, which was the same as the actual forward model, to 12.4 mm for BSCR = 120. For the sLORETA method, the error ranges from 2.5 mm to 9.7 mm. Fig. 2 (b) shows the Tukey's pairwise comparison results. Each BSCR value was compared with the rest BSCR values for either effect in localization error. Underlines denote BSCR values with insignificant difference at 95% confidence interval. Take dipole estimation method for example, BSCR= 25 and BSCR = 15 were not significantly different, because the two shared an underline. But they were both significantly different from all other values. The general trend was that the localization error was the smallest when the BSCR in the inverse model matches best with the forward one. In this case it was BSCR = 20.

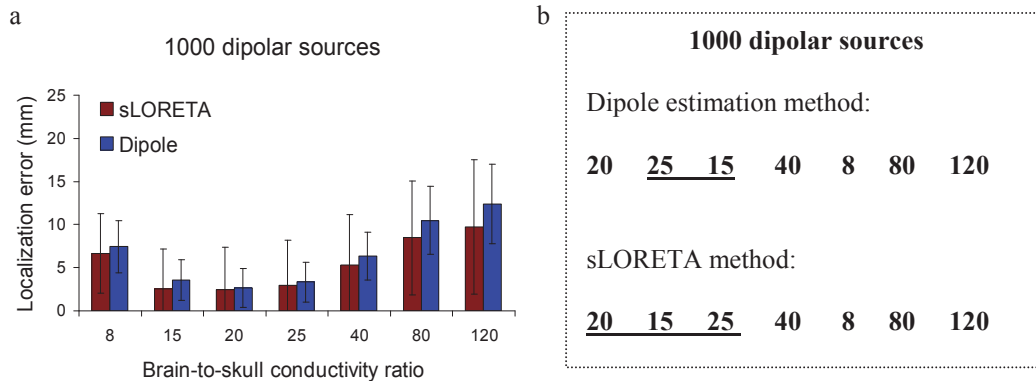


Figure 2. (a) Source localization results for 1000 dipolar sources, using both dipole estimation and sLORETA source reconstruction algorithms. (b) Tukey's pair-wise comparison results with $p < 0.05$. The numbers denotes seven BSCR values. Underlines denote BSCR values that have insignificant difference among them at 95% confidence interval.

3.2. 200 Distributed Sources Simulation

Simulation results for 200 distributed cortical sources with different inverse BSCR values are shown in Fig. 3 (a). The mean localization error for dipole estimation method ranges between 6.6 mm for BSCR = 20, to 12.8 mm for BSCR = 120. For sLORETA method, the error ranges from 6.9 mm for BSCR = 20 to 11.6 mm for BSCR = 120. Fig. 3 (b) shows the Tukey's pairwise comparison results. Different from the 1000 dipolar simulation, the difference among different distributed source models were smaller. More values appeared to have insignificant difference. For example, results from dipole estimation, BSCR= 20, 15, 25 were not significantly different among the three. But BSCR = 80 and 120 were still significantly different from the rest values for dipole estimation method.

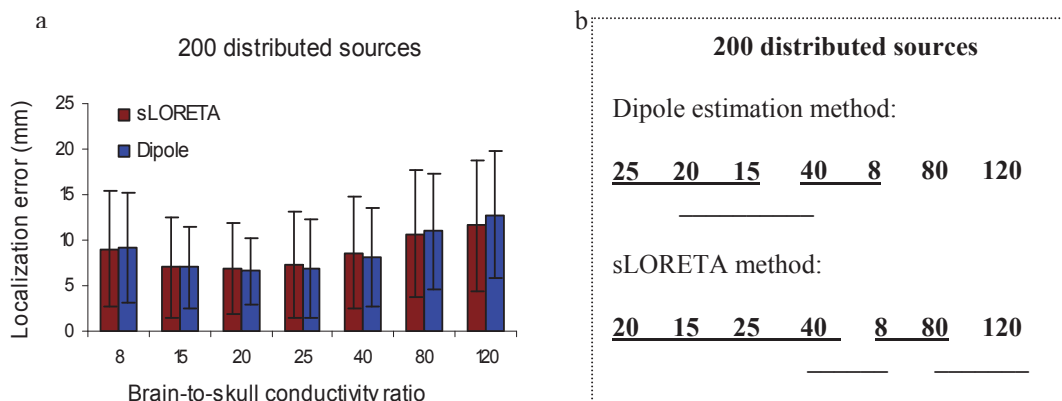


Figure 3. (a) Source localization results for 200 distributed sources, using both dipole estimation and sLORETA source reconstruction algorithms. (b) Tukey's pair-wise comparison results for 200 distributed sources with $p < 0.05$. The numbers denotes seven BSCR values. Underlines denote BSCR values that have insignificant difference among them at 95% confidence interval.

4. Discussion

The aim of the present study was to examine the relationship between conductivity uncertainties and EEG source localization accuracy by using a simulation protocol. In this study, we evaluated seven

previously reported BSCRs: 8, 15, 20, 25, 40, 80, and 120. The simulation results suggested that the BSCRs had certain influence over the accuracy of EEG source localization, which may have potential implications for clinical applications. When the inverse BSCR values deviate greatly from the BSCR value used in forward model, the resulted localization error were proportionally bigger, as seen in the case of BSCR = 80 and 120. Based on current study, the dipolar forward model appear to be more sensitive to different BSCR values than the distributed forward model, as more significantly different BSCR pairs can be seen from the dipolar model. However, distributed models might resemble actual situations in clinical application better, as EEG can be generated by a large number of distributed neurons instead of a focused dipolar point. More simulations should be performed for various conductivity ratios in the forward model at different noise levels.

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