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Brain sources estimation based on EEG and computer simulation technology (CST)

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ABSTRACT

EEG source estimation aims to provide precise information about the location of active brain source that corresponds to the measured signals. The accuracy of EEG forward model significantly influences the accuracy and performance of the inverse problem. In this research, we propose a new method to model head volume conductor and generate a leadfield matrix. The solution is based on employing electromagnetic simulation (CST electromagnetic software) to generate a leadfield matrix of a realistic head. The geometrical data consist of three compartments (Brain, Skull, and Scalp) obtained from real human MRI data. Finite Element Method (FEM) was used in the CST low frequency solver to generate the forward model. We were able to demonstrate the use of the electromagnetic simulation solvers in solving the EEG forward problem. The result has been validated by comparing the scalp voltage potential distribution obtained using CST with scalp potential calculated using FieldTrip (EEG/MEG open source). To further validate the proposed technique, an inverse solution was able to estimate the location of active dipoles within brain successfully based on the calculated leadfield matrix using CST.

1. Introduction

In neural imaging, it is important to estimate the position of the source that corresponds to the measured EEG signal. EEG source localisation is used to perform activity source estimation in the brain. In source localisation, there are two models. First, the forward model calculates the potentials on the scalp for given electrical sources in the brain. Second, for a given forward model we can compute the inverse model which is finding the responsible source that caused the measured potential at the electrode side [1]. An accurate forward model is required in many applications in both medical neuro-imaging and commercial applications such as BCI. The forward problem, in which the head model is created, has a significant influence on the inverse model as they both map the source within the brain and their potential contribution on the scalp [2]. Therefore, modelling the head appropriately will lead to optimal results in the inverse solution. This will lead to an accurate source localisation which is very important in neuroimaging to identify the source of activity for given EEG measurements [3]. To obtains meaningful information from the measured EEG signal, it needs to be related to the neural activity within the brain. There is no straightforward relation between the EEG measured signal and neural activity and the processes are very complicated [4]. EEG measures the electrical potential on the scalp that is caused by large numbers of neurones, and to link the measured signal to the corresponding active area we need to understand how this signal is formed. Therefore, to analyses the measured signal we not only need to know the physical meaning of such a signal, but also, we need to have a precise understanding of how the brain works, and this will help in the interpretation of EEG measurements. Therefore, brief biological description of the neural cells will be explored to give a deep understanding of the active brain sources. This will help with more advanced analysis such as source estimation [4,5].

Identifying the location of the active source of the neural activity is the key point in many studies that involve electroencephalography (EEG) measurements. The complex task is that the measured signal is a result of a large number of active brain sources. Therefore, relating the measured EEG potential with it is corresponding active sources would be a major challenge. The forward problem and the inverse problem should be solved to be able to localize the source of activity. There are also several advanced processing methods such as classifications and denoising have been proposed which may improve the process of signal analysis [6]. However, in this paper we are only interested in the forward modelling process. In the scope of the forward solution, the problem is well documented in the literature where many analytical and numerical solutions have

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been proposed to generate the head conductor model. An accurate volume conductor model is crucial to describe the signal propagation of the active neural cells. The volume conductor model has a significant influence on the reconstructed source time courses as well as on source connectivity analysis [7]. Therefore, producing accurate head model will have a significant impact on the brain signal studies. There are many ways to model the volume conductor. The spherical head model was the first proposed volume conductor model in which the head is assumed to be a homogeneous sphere [8]. However, it was discovered that brain tissue is not homogenous where skull tissue has very low conductivity compared with other brain compartments [9–11,5]. Therefore a three-shell concentric sphere representing brain, skull and scalp has been introduced for more realistic representation that has a semi-analytical solution [12]. However, this multi-shell spherical model is only an approximation to the real head model. Therefore, later, more advanced numerical methods such as Boundary Element Method (BEM) [13], Finite Volume Method (FVM) [14], Finite Difference Method (FDM) [15], and Finite Element Method (FEM) [16] have been suggested for realistic representation of the human head where the geometrical representation is generated depending on MRI data. The BEM and FEM are the mostly used in modelling head conductor volume.

Boundary Element Methods (BEM) are used for calculating the surface potential of the interface between compartments generated by a current source in piecewise homogenous volume [17]. The drawback in BEM is assuming isotropic conductivity which is not the case in the brain tissue. Therefore Finite Element Methods (FEM) is introduced to tackle both inhomogeneity and anisotropicity of brain tissue [18]. In the FEM technique, the entire brain will be digitized into small elements (tetrahedral) to solve the 3D volume conductor. As the number of nodes is very large in FEM compared with BEM, this makes FEM a very computationally-intensive method in both direct and subtraction approach [18]. The FEM method has also enabled researchers to include additional brain compartment other than brain, skull, and scalp. CSF, grey matter and white matter, are also included in FEM models and their influence on the EEG/MEG forward problem has been widely investigated [19,20]. Recently, researchers studied the effect of dura layer, which covers the brain and located between the highly resistive skull bone compartment above and CSF, on the current flow and scalp potential distribution [21]. Very recent research suggested that cerebral blood vessels cloud has a considerable effect on modelling the head conductor volume and ignoring the cerebral blood vessels may cause focal localization errors of approx. 5–15 mm [22]. Increasing the number of the compartment will make FEM very computationally intensive. To reduce the required computational resources for FEM head conductor model, a reciprocity approach has been proposed in which the roles of dipole (atomic structure of the primary current density distribution) and sensor can be reversed [23].

In forward problem, it is well known that FEM achieves the most accurate results over the other methods as it calculates the conductivity in three dimensions [3]. To solve the forward problem using FEM method, there are many available open sources, such as EEGLab-NFT [24], OpenMEEG [25], MNE [26], Brain Storm [27], and FieldTrip [28]. For instance, FieldTrip has it is own built-in functions that include the aforementioned analytical and numerical methods, with some of them based on internal MATLAB codes and others based on external sources such as SimBio for FEM calculation [29]. The variation in the results between the available packages gives a great motivation to investigate other possible solvers. The main aim of this research study is to investigate new possible methods and tools to solve the EEG forward problem. In this research paper, we suggested and investigated a novel approach and tool for generating FEM forward model for EEG study. Computer Simulation Technology (CST) is proposed to be used in generating head conductor model in this research paper. This technology has been intensively used to offer efficient computational solutions for antenna design, 3D electromagnetic design and simulation of large scale problems, EMC, BioEM, RF, and microwave problems. However, to the best of our knowledge, no one has applied the CST technology in brain signal analysis. Therefore, Computer Simulation Technology (CST) has used for the first time in this study to generate a realistic head conductor volume and EEG forward solution. The research target is to explore the new proposed method and validate it's used in generating the head conductor model and solving the EEG forward problem. The validation of the proposed approached will be achieved in two ways. First, comparing the FEM forward solution (scalp potential distribution of a realistic head) obtained by the proposed CST technology with forward result (scalp potential distribution of a realistic head) obtained by a well-known tool in the literature called Fieldtrip. Second, use the inverse model to estimate the location of an active dipole with pre-known location that virtually (in the simulation model) placed inside the head geometry. Then comparing the estimated location with the actual pre-known location to confirm the effectiveness of the proposed approach. The result would be extremely valuable by way of discovering new methods of modelling head conductor volume. Regarding the inverse modelling, it is not the focus of this project and we only used beamforming methods to reconstruct the active source to validate our proposed method for the forward modelling.

2. Mathematical models

2.1. Neural cell electrical model

Brain activity involves processes such as metabolism, glucose, or dopamine synthesis [5]. These local hemodynamically changes will enable us to study the neural activity – when neurones become active they result in changes in the blood flow and oxygen level which is indicative of neural activity. Each neurone membrane is built from layers which are electrically isolated to form the interior and exterior of the cell. Three ions are present in the membrane: sodium (Na^+) and chloride ($C1^-$) outside the cell, and potassium (K^+) inside, in which these ions can leave and enter the cell through an ionic channel [30]. When the concentration inside the cell is high, the K^+ ions will move from inside to outside (lower concentration to higher concentration) through the ionic channel. This means a positive charge will move from inside to outside giving rise to an electrical field across the membrane. To reach the equilibrium such an electrical field will introduce opposed detraction moving phenomena in which a positive charge moves towards an area with a lesser positive charge. The potential across the membrane is the difference between internal and external potential $V_m = V_{in} - V_{out}$ (approximately −70 mV at rest).

The potential at equilibrium for a given cell is called *equilibrium potential* (E) in which the number of positive charges inside the cell is higher than outside. When $V_m = E_k$ no current will flow through the ionic channel, when $V_m > E_k$ positive current will pass through ($I_k > 0$), and when $V_m < E_k$ negative current will flow ($I_k < 0$). Fig. 1 shows the action potential of the membrane [30].

An equivalent circuit can be derived to represent membrane activity. Fig. 2 illustrates the equivalent circuit diagram of a membrane in which the membrane is modelled as a resistor (g_k) and reverse potential (E_k) in series and all parallel with a capacitor (C_m). The flowing current will be proportional to the number of positive charges moving from inside to outside the cell or vice versa [30].

In this case, Kirchhoff's Law can be applied to represent the membrane temporal potential as in Eq. (1).

$$C_m \frac{dV_m}{dt} + g_k (V_m - E_k) = 0 \qquad (1)$$