Journal of Neuroscience Methods 274 (2016) 94–105

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

The inverse problem in electroencephalography using the bidomain model of electrical activity

Alejandro Lopez Rincon*, Shingo Shimoda

RIKEN BSI-TOYOTA Collaboration Center, 2271-130 Anagahora, Shimoshidami, Moriyama-ku, Nagoya, Aichi 463-0003, Japan

HIGHLIGHTS

- The EEG inverse problem is solved using the bidomain model.
- A spatial comparison is made with fMRI using the linkRBrain platform.
- Accuracy is increased in comparison with other methods (MNE and LORETA).

ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form
28 September 2016
Accepted 28 September 2016
Available online 11 October 2016

Keywords:
EEG
Bidomain
Regularization
Inverse problem

ABSTRACT

Background: Acquiring information about the distribution of electrical sources in the brain from electroencephalography (EEG) data remains a significant challenge. An accurate solution would provide an understanding of the inner mechanisms of the electrical activity in the brain and information about damaged tissue.

New Method: In this paper, we present a methodology for reconstructing brain electrical activity from EEG data by using the bidomain formulation. The bidomain model considers continuous active neural tissue coupled with a nonlinear cell model. Using this technique, we aim to find the brain sources that give rise to the scalp potential recorded by EEG measurements taking into account a non-static reconstruction.

Comparison with Existing Methods: We simulate electrical sources in the brain volume and compare the reconstruction to the minimum norm estimates (MNEs) and low resolution electrical tomography (LORETA) results. Then, with the EEG dataset from the EEG Motor Movement/Imagery Database of the Physiobank, we identify the reaction to visual stimuli by calculating the time between stimulus presentation and the spike in electrical activity. Finally, we compare the activation in the brain with the registered activation using the LinkRbrain platform.

Results/Conclusion: Our methodology shows an improved reconstruction of the electrical activity and source localization in comparison with MNE and LORETA. For the Motor Movement/Imagery Database, the reconstruction is consistent with the expected position and time delay generated by the stimuli. Thus, this methodology is a suitable option for continuously reconstructing brain potentials.

1. Introduction

Neural processes are generated by the propagation of electrical activity in the brain. This activity produces electrical potentials that can be measured through electrodes in various positions on the scalp, a technique referred to as electroencephalography (EEG). This voltage distribution on the scalp is generated from the extracellular current by the post-synaptic potentials in the apical dendrites of pyramidal neurons inside the brain. EEG signals, in comparison with other brain imaging techniques, have the advantage of high temporal resolution, but they have a small amplitude (on the order of hundred of μV) and are highly susceptible to noise.

The electrical activity of the brain is described by the volume conductor model with current sources using Poisson's equation coupled with Neumann and Dirichlet boundary conditions (Hallez et al., 2007a). Simulating the potentials at the electrode positions from current sources inside the brain is known as the EEG forward problem; inference of the position of the current sources from electrode potentials is known as the EEG inverse problem or the neural source imaging problem (Grech et al., 2008; Brannon et al., 2008).

The EEG inverse problem is fundamental in neuroscience, as it gives insight about spatial and temporal activity in the brain for different tasks. An accurate solution of the neural source imaging

* Corresponding author.
E-mail addresses: alejandro.lopezrn@hotmail.com (A. Lopez Rincon), shimoda@brain.riken.jp (S. Shimoda).

http://dx.doi.org/10.1016/j.jneumeth.2016.09.011

problem can contribute to understanding the inner workings of the brain and to pinpointing regions with conductivity anomalies that might indicate damaged tissue (Pascual-Marqui, 1999). The EEG inverse problem is an ill-posed problem; thus, there is not a unique solution. To reconstruct an approximate solution, we need regularization techniques and methods like minimum norm estimates (MNE) (Grech et al., 2008) and low resolution electrical activity tomography (LORETA) (Grech et al., 2008; Pascual-Marqui et al., 2002, 1999). These methods consider the relationship between the current sources and the measured potentials assuming a quasi-static approximation expressed by the lead field matrix (Weinstein et al., 1999).

In this work, we propose to solve the EEG inverse problem by using the bidomain model (Sundnes, 2007). The bidomain is a reaction-diffusion model for the electrical activity of the heart and takes into account the anisotropy of the intracellular and extra-cellular cell domains. Compared with other methods, it does not impose a quasi-static assumption and considers an electrical model of a cell described by a series of ordinary differential equations. The bidomain model is typically used to describe the heart's electrical activity, but it was adapted as an alternative method to solve the EEG forward problem in Yin et al. (2013) and Szmurlo et al. (2007).

Starting from the standard bidomain formulation, we coupled the model to the node lead field matrix and created the necessary operators to solve the inverse problem, which gives a relationship between the scalp potentials and the stimuli in the cell model. Compared with other source localization methods, the bidomain method maintains the continuum assumption. Instead of applying regularization techniques to the current sources, we apply the regularization to the stimuli that produce the current sources. This is similar to the approach explained in detail in Lopez-Rincon et al. (2015), but adapted to the brain.

2. Methods

2.1. Mathematical background of bidomain formulation

To explain the bidomain formulation, it is necessary to give a brief overview of the lead field matrix, MNE, and LORETA methods for the EEG source localization problem.

2.1.1. The lead field matrix

The EEG-measured neural activity from the brain can be described by Poisson's equation for electrical conduction (De Munck et al., 1988; Weinstein et al., 1999)

$$\nabla \cdot \sigma \nabla \Phi = -I \quad \text{in} \quad \Omega, \tag{1}$$

with the boundary condition

$$\sigma \nabla \Phi \cdot \mathbf{n} = 0 \quad \text{on} \quad \Gamma, \tag{2}$$

where Φ represents the electrostatic potentials, σ the conductivity, I the current sources in the brain volume, $\mathbf{n}$ the outward normal vector, Γ the surface area of the head, and Ω the volume of the head. In EEG modeling, we consider the normal component of the current density to be zero as a boundary condition. Using finite element method (FEM) discretization in a 3D mesh, we can write Eqs. (1) and (2) as a system of linear equations, which may be written in matrix form (Sundnes, 2007; Gockenbach, 2006):

$$\mathbf{A}\mathbf{u} = \mathbf{I} \tag{3}$$

where

$$\mathbf{A}_{ij} = \int_{\Omega} \nabla \phi_i \cdot \nabla \phi_j,$$

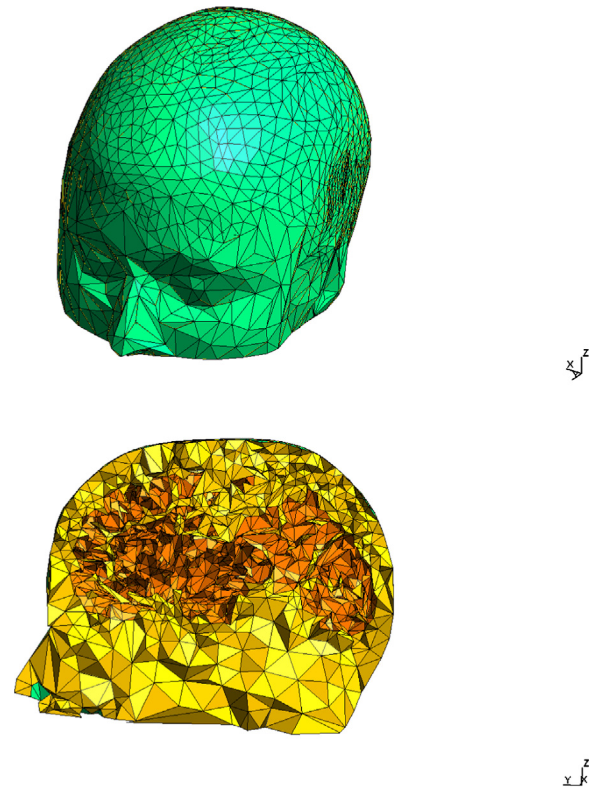

Fig. 1. *Top*: 3D mesh of a head divided into tetrahedra using FEM. In this geometry, the head is the domain Ω and the outer surface is the domain Γ. *Bottom*: FEM discretization of the domains.

$$\mathbf{I}_i = \int_{\Omega} I\phi_i,$$

and $\mathbf{u}$ is a vector with the scalar node values of the potential, for basis functions ϕ_i and ϕ_j (Fig. 1).

The model described in Eq. (1) is known as the pure Neumann problem and has no unique solutions; however, applying additional constraints—for example, reducing it to Laplace's equation (Johnson and MacLeod, 1998), fixing one electrode on the scalp to zero (Becker et al., 1982; Troparevsky and Rubio, 2003) or using the method described in Bochev and Lehoucq (2005)—gives a unique solution. From the system in Eq. (3) we can construct the lead field matrix $\mathbf{L}$ which gives a projection between the current sources in the brain volume and the measured electrical activity in the scalp:

$$\mathbf{r} = \mathbf{L} \cdot \mathbf{s} + noise. \tag{4}$$

Here, $\mathbf{L}$ is the lead field matrix, $\mathbf{r}$ is a vector of the measured potentials on the head, and $\mathbf{s}$ a vector of the current sources in the brain volume. For our tests, we use the node lead field matrix as described in Weinstein et al. (1999) and thereby reconstruct not only the current sources, but also the potential in the brain volume. The lead field matrix will typically be non-invertible as it depends on the quantity of sources and recordings. Thus, it is necessary to use regularization methods to solve the inverse problem

$$\min_{\mathbf{s}} \|\mathbf{L}\mathbf{s} - \mathbf{r}\|. \tag{5}$$

2.1.2. Minimum norm estimates

The MNE (Grech et al., 2008) method is suitable for reconstructing the activity on the cortical surface. This method will give the minimum energy solution (closest to zero). MNE does not have an inclusion of priori restrictions that allow approximating a solution closer to the actual physical behavior in the brain from the set of