MSc course: Recording and Processing of Brain Signals (Fall/Winter 2016)
Notes by A. Koulouri

A TUTORIAL ON EEG SOURCE LOCALIZATION

THEORY

Introduction

Source localization in human brain is a potential problem which falls into the complex real world problems due to functional and biological complexity of the brain, as well as clinical limitations of collecting EEG from infinitely many subjects. It is well established that electrical activities recorded over the surface of the scalp is due to the combined activities of single neurons in the brain. Any spontaneous activity of the brain, sensory stimulation, cognitive activity, or the generation of motor output may give rise to such neuronal activities. Source localization in human brain, then, involves the localization and identification of such underlying neuronal generators inside the brain. Despite rich and diverse research in the area, the problem remains to be an unsolved inverse problem in the brain research. The importance of the problem lies in the direct association between the underlying neuronal activities inside the brain and their neurophysiological function which can be observed as EEG or MEG. The difficulty, on the other hand, lies in the lack of suitable methodologies in the inverse mapping, and modeling limitations. Thus, it falls into the class of ill-posed inverse problems unless some constraints about the type of source and head models are imposed.

In this text, we present a brief tutorial on EEG source localization problem. For a more comprehensive understanding of the problem, readers are referred to the relevant literature cited in the following sections.

Forward and Inverse Mapping

Literature in source localization suggests that, the non-uniqueness of the problem was known even before the first EEG recordings had been made [1], i.e. a multitude of source configurations may give rise to the same potential distributions over the scalp. The only way to eliminate the non-uniqueness of the problem is to postulate a priory models for both head and underlying sources. Therefore the solution space is restricted to the model space. Once these assumptions are made, the problem reduces to forward mapping, and inverse mapping (Figure 1). Forward mapping is computing surface (scalp) potentials over the head model due to assumed source model. In a mathematical formulation, the most general expression to calculate scalp potentials can be expressed as [2] where $v(x,t)$ is the potential at time t at some observation point p within the head, and $J(xi,t)$ is the active sources at time t and point xi within the source volume. The function $L(p,xi)$ represents the transfer function from the sources to the potentials in the observation points (also called lead-field function). Then $v(\mathrm{x},t)$ represents full spatiotemporal information about the underlying sources.

Inverse mapping, on the other hand, is to find underlying source parameters, i.e. location and orientation in the case of current dipole, a putative parametric source

model, by minimizing a cost function between model generated surface voltages and measured EEGs.

Inverse mapping depends on the forward mapping, since the forward model determines the goodness of fit.

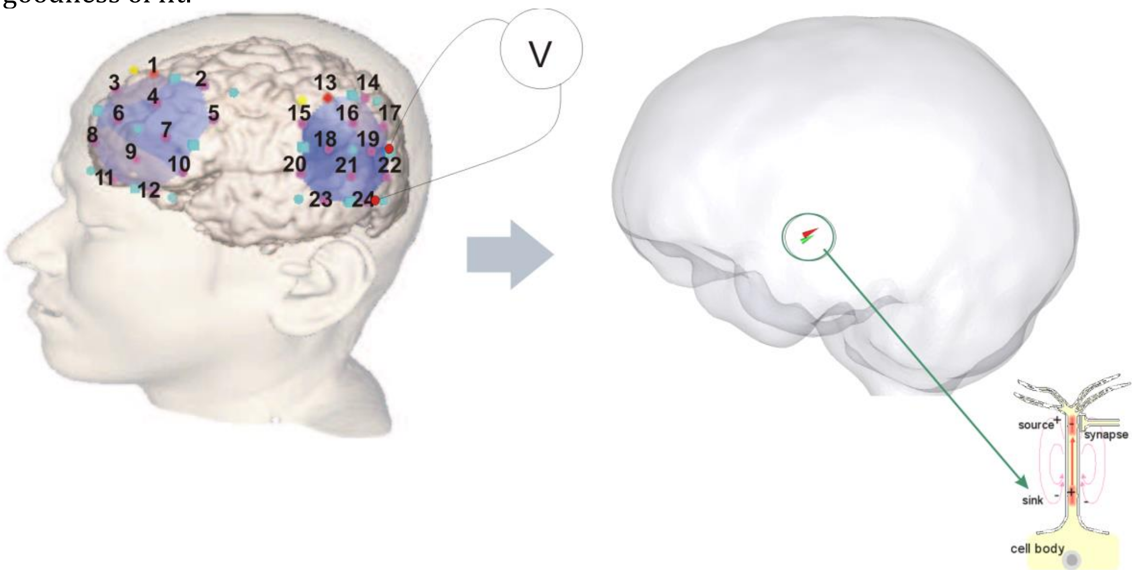

Figure 1: An Illustration of Source Imaging Problem in Human Brain. Forward mapping is to calculate surface potentials over some number of channels. The essential part of the problem is inverse mapping, where underlying sources are to be mapped using EEGs.

The literature on the source localization is diverse and rich. Fender [3] presents the development in source localization focusing on the head modeling issues in his review paper, whereas Scgherg [4] gives a good tutorial treatment of the theory and methodology focusing on dipole sources. For a more comprehensive and introductory level, see review by Oosterom [2] and Hamalainen [5]. The idea of representing underlying neuronal activities by a current dipole first appeared in the work of Brazier [6]. After the dipole source is accepted as a putative source model, the localization and orientation of these sources have begun to be of interest to the several researchers [7] [8] [9]. The techniques in the inverse mapping involve first deciding on some geometrical and electrical model of the head and then assuming initial set of parameters for source model. The distribution of the potential that the dipoles produce over the surface of the head model is then calculated over the pre-determined surface locations (forward mapping). The computed potential values is compared against actual potential values over the corresponding measurement channels. Then, the parameters of the source models are updated in an iterative manner (inverse mapping), such as Marquardt algorithm [10], until the best fit is obtained.

Kavanagh *et. al.* [11] presented a quantitative analysis of the methods in source localization over both homogeneous and inhomogeneous sphere. He employed equivalent current dipole as source model in the visual cortex human visually evoked scalp potentials. Nunez [12], on the other hand, gave a detailed analysis of the localization of brain activities by using EEGs. His analysis included several source types and head models. Rush *et. al.*, [13] addressed the problem of electrode sensitivity in the inverse mapping. A more theoretical study of the uniqueness of the problem is given by Amir [14]. Several others also addressed the problem of improving the inverse mapping by giving a comparative analysis of EEGs and MEGs, as well as using medical imaging, such as MRI, as supplementary information [15] [16] [17] [18] [19] [20].

The problem is also studied from the optimization point of view. Mosher [19], in his recent work, studied the problem under the multiple dipole models using spatio-temporal MEG data. He presented a subspace scanning method, a suboptimal but faster approach, in inverse mapping. Tsche et al. [21] [22], on the other hand, studied the inverse mapping by describing signal space projection in her recent work.

Modeling Issues

Selection of head and source models is a crucial issue in source localization since both forward and inverse mapping depends on the model. Indeed, the modeling issue is the first step in studying the source localization.

Different source models are employed in source localization/imaging. Single dipole model is a putative source model widely used in the literature. It is valid as long as neuronal activity inside the human brain is confined to a small area with respect to the measurement points [4] [5]. Among the other models used as a source models are: sheet source model [23]; where number of dipoles are placed on a finite sheet plane, disc model [24]; where dipoles are placed an a disc with a finite radius, curved source [23]; which is the folded sheet source, and line source [24]; where dipoles are allied in a line. Cuffin [24] presented moving dipole solution in inverse mapping. He fitted several source types, such as disc source, line source, and two-dipole source, by a moving single dipole and observed the goodness of fit as a function of radius of the disc in the disc source, length of the line in the line source case, and orientation of dipoles in the two-dipole case. Similar analysis can also be found in [25]. Several aspects of spatio-temporal dipole model is studied in [4] [26].

Head shapes in the literature varies from spherical head to finite element head model. Spherical head models may have single or multiple concentric layers with different inhomogeneity in each layer [3] [11] [16]. Cuffin [27] studied the effects of head shape using both EEG and MEG in inverse mapping, and analyzed the localization error with respect to head shape. Menninghaus [28] also addressed the head model problem by comparing realistic versus spherical head model.

References

1

H. Helmholz, ``Ueber einiger gezetze der vertailung elektrischer strome in korperlichen leiter mit anwendungauf die thierishch electrischeb versuche,'' *Pogg Ann Physik Chemie*, vol. 33, pp. 353-377, 1853.

2

A. V. Oosterom, ``History and evaluation of methods for solving the inverse problem,'' *Journal of Clinical Neurophysiology*, vol. 8, no. 4, pp. 371-380, 1991.

3

D. H. Fender, ``Models of teh human brain and the surrounding media: Their influence on the reliability of source localization,'' *Journal of Clinical Neurophysiology*, vol. 8, no. 4, pp. 381-390, 1991.

4

M. Scherg, ``Fundamentals of dipole source potential analysis,'' in *Auditory Evoked Magnetic Fields and Electric Potentials* (G. F. Hoke and M. Romani, eds.), vol. 6, pp. 40-69, 1990.

5

M. Hamalainen, R. Hari, R. J. Ilmoniemi, J. Kunuutila, and O. V. Lounasmaa, ``Magnetoencephalography: Theory, instrumentation, and applications to noninvasive studies of the working human brain.,'' *Rev. Modern Phys.*, vol. 65, pp. 413-497, 1993.

6

M. A. B. Brazier, ``A study of the electric field at teh surface of the head,'' *Electroencephalography and Clinical Neurophysiology*, vol. 2, pp. 38-52, 1949.

7

J. C. Shaw and M. Roth, ``Potential distribution analysis i: A new technique for the analysis of electrophysiological phenomena,'' *Electroencephalography and Clinical Neurophysiology*, vol. 7, pp. 273-84, 1955.

8

C. D. Geisler and G. L. Gerstein, ``The surface eeg in relation to its sources,'' *Electroencephalography and Clinical Neurophysiology*, vol. 13, pp. 927-934, 1961.

9

D. Lehmann, R. N. Kavanagh, and D. H. Fender, ``Field studies of averaged visually evoked eeg potentials in a patient with a splitchiasm,'' *Electroencephalography and Clinical Neurophysiology*, vol. 26, pp. 193-199, 1969.

10

D. W. Marquardt, ``An algorithm for least-squares estimation of nonlinear parameters,'' *J. Soc. Industrial and Appl. Math.*, vol. 11, pp. 413-441, 1963.

11

R. N. Kavanagh, T. M. Darcey, D. Lehmann, and D. H. Fender, ``Evaluation of methods for three-dimensional localization of electrical sources in the human brain,'' *IEEE Transections on Biomedical Engineering*, vol. BME-25, pp. 421-429, September 1978.

12

P. L. Nunez, ``Localization of brain activity with electrocardiography,'' *Advances in Neurology*, vol. 54, pp. 39-65, 1990.

13

S. Rush and D. Driscoll, ``Eeg electrode secsitivity-an application of reciprocity,'' *IEEE Transections on Biomedical Engineering*, vol. BME-16, pp. 15-22, January 1969.

14

A. Amir, ``Uniqueness of the generators of brain evoked potential maps,'' *IEEE Transections on Biomedical Engineering*, vol. 41, pp. 1-11, January 1994.

15

M. Balish and R. Muratore, ``The inverse problem in electrocardiography and magnetoencephalography,'' *Advances in Neurology*, vol. 54, pp. 79-88, 1990.

16

Y. Salu, L. G. Cohen, D. Rose, S. Sato, C. Kufta, and M. Hallett, ``An improved method for localizing electric brain dipoles,'' *IEEE Transections on Biomedical Engineering*, vol. 37, pp. 699-705, July 1990.

17

P. L. Nunez, ``Generation of human eeg by a combination of long and short range neurocortical interactions,'' *Brain Topography*, vol. 1, no. 3, pp. 199-215, 1989.

18

A. M. Dale and M. I. Sereno, ``Improved localization of cortical activity by combining eeg and meg with mri cortical surface reconstruction: A linear approach,'' *Journal of Cognitive Neuroscience*, vol. 5, no. 2, pp. 162-176, 1993.

19

J. C. Mosher, P. S. Lewis, and R. M. Leahy, ``Multiple dipole and localization from spatio-temporal meg data,'' *IEEE Transections on Biomedical Engineering*, vol. 39, no. 6, pp. 541-557, 1992.

20

K. Sekihara, Y. Ogura, and M. Hotta, ``Maximum-likelihood estimation of current-dipole parameters for data obtained using multichannel magnetometer,'' *IEEE Transactions on Biomedical Engineering*, vol. 39, no. 6, pp. 558-562, 1992.

21

C. D. Tsche, M. A. Uusitalo, R. J. Ilmoniemi, M. Huotilainen, M. kajola, and O. Salonen, ``Signal-space projections of meg data characterize both distributed and well-localized neuronel sources,'' *Electroencephalography and Clinical Neurophysiology*, vol. 95, pp. 189-200, 1995.

22

C. Tsche and M. kajola, ``A comparision of the localization of spontaneous neuromagnetic activity in the frequency and time domains,'' *Electroencephalography and Clinical Neurophysiology*, vol. 87, pp. 408-416, 1993.

23

K. Ueno, K. Iramina, and S. Ueno, ``A source model with 2-dimentional spread of electrical activity in the human brain,'' in *Proc. of IEEE EMBS*, pp. 177-178, 1994.

24

B. N. Cuffin, ``A comparision of moving dipole inverse solutions using eegs and megs,'' *IEEE Transections on Biomedical Engineering*, vol. 32, no. 11, pp. 905-910, 1985.

25

Y. Okada, ``Discrimination of localized and distributed current dipole sources and localized single and multiple sources,'' in *Biomagnetism: applications and theory* (a. a. H. Weinberg, ed.), vol. 1, (Elmsford, NY), pp. 266-272, Pergamon, 1985.

26

M. Scherg and D. V. Cramon, ``Two bilateral sources of the late aep as identified by a spatio-temporal dipole model,'' *Electroencephalography and Clinical Neurophysiology*, vol. 62, pp. 32-44, 1985.

27

B. N. Cuffin, ``Effects of head shape on eegs and megs,'' *IEEE Transections on Biomedical Engineering*, vol. 37, pp. 44-52, January 1990.

28

E. Menninghaus, B. Lutkenhoner, and S. Gonzalez, ``Localization of a dipolar source in a skull phantom: Realistic versus spherical model,'' *IEEE Transections on Biomedical Engineering*, vol. 41, pp. 986-989, October 1994.

29

U. R. Abeyretne, Y. Kinouchi, H. Oki, F. Shichijo, and K. Matsumoto, ``Artificial neural networks for source localization in human brain,'' *Brain Topography*, vol. 4, no. 1, pp. 3-20, 1991.

30

W. M. Lippe, T. Fuering, A. C. Jankrift, and R. Hohenstein, ``Frequency-domain localization of intrecerebral dipole sources,'' in *Intelligent Engineering Systems Through Artificial Neural Networks* (C. H. Dagli, M. Akay, C. L. P. Chen, B. Fernandez, and J. Gosh, eds.), vol. 4, (New York, NY), pp. 747-752, ASME Press, 1994.

31

B. He, C. Poon, and R. J. Cohen, ``A new electrocardiography inverse solution by means of neural networks,'' in *Procedings of the 15th International Conference of IEEE EMBS Society*, pp. 292-293, 1993.

32

M. Sonmez, M. Sun, X. Yan, and R. J. Sclabassi, ``On the error analysis of artificial neural networks in brain source localization,'' in *Intelligent Eng. Sys. Through Artificial Neural Networks* (C. H. Dagli, M. Akay, C. L. P. Chen, B. R. Fernandez, and J. Ghosh, eds.), vol. 5, pp. 687-692, ASME Press, 1995.

33

M. Sonmez, M. Sun, X. Yan, and R. J. Sclabassi, ``Extension of a training set for artificial neural networks and its application to brain source localization,'' in *Proc. of the IEEE International Conference on Neural Networks*, vol. 2, (Washington, DC), pp. 635-640, IEEE, June 3-6 1996.

34

H. Mizuta, K. Yana, B. He, and R. J. Cohen, ``Neural network size determination for electrocardiography inverse dipole solution,'' in *Procedings of the 16th International Conference of IEEE EMBS Society*, (Baltimore, MD), pp. 1085-1086, November 1994.

35

S. Haykin, *Neural Networks: A Comprehensive Foundation*. New York: Macmillan Colege Publishing Co., 1994.