北京航空航天大学四年级博士生和五年级直博生
学校奖学金申报表

（请按填表说明填写，本表填写的内容必须为非涉密可公开！）

<table>
<tr><td>姓　名</td><td colspan="2">胡业刚</td><td>学　号</td><td>BY1510114</td><td>指导教师</td><td colspan="2">张冀聪</td></tr>
<tr><td>类　别</td><td colspan="4">☑ 三年级博士生　☐ 四年级直博生</td><td>学科/专业</td><td colspan="2">生物医学工程</td></tr>
<tr><td rowspan="3">承担科研任务情况</td><td colspan="3">项目名称</td><td>课题来源</td><td>课题负责人</td><td colspan="2">本人承担的具体工作</td></tr>
<tr><td colspan="3">脑功能疾病精准诊断和个体化治疗的关键技术及标准化流程的研究</td><td>国家科技部重点研发计划</td><td>张冀聪</td><td colspan="2">设计脑磁图定位算法、癫痫致痫灶定位</td></tr>
<tr><td colspan="3">改进的多重信号分类算法在脑磁图的颞叶癫痫致痫灶定位中的应用研究</td><td>脑功能疾病调控北京市重点实验室</td><td>胡业刚</td><td colspan="2">负责项目的实施</td></tr>
<tr><td rowspan="9">已取得研究成果（论文、专利、获奖等）</td><td colspan="3">论文题目</td><td>本人排名</td><td>发表年月</td><td>期刊（会议）名称</td><td>被检索类型</td></tr>
<tr><td colspan="3">Deep source localization with MEG based on sensor array decomposition and beamforming</td><td>1</td><td>2017.8</td><td>sensors</td><td>SCIE 源</td></tr>
<tr><td colspan="3">MEG source imaging algorithm for finding deeper epileptogenic zone</td><td>1</td><td>2017.9</td><td>ICSEE</td><td>EI 源</td></tr>
<tr><td colspan="3">Low-rank matrix recovery for source imaging with MEG</td><td>1</td><td>2018.5 (Accept)</td><td>Optics and Laser Technology</td><td>SCI 源</td></tr>
<tr><td colspan="3">专利名称</td><td>本人排名</td><td>发布年月</td><td>专利号</td><td>专利类型</td></tr>
<tr><td colspan="3"></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">获科技成果奖励名称</td><td>本人排名</td><td>获奖年月</td><td>证书编号</td><td>奖励级别</td></tr>
<tr><td colspan="3"></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>本人承诺</td><td colspan="7">本人所填写的以上内容均为真实情况。
本人签字：
年　月　日</td></tr>
<tr><td>导师意见</td><td colspan="7">同意 / 不同意 该同学申报学校奖学金。
导师签字：
年　月　日</td></tr>
</table>

学院学位评定分委员会意见	同意 / 不同意 该同学获得学校奖学金。 签字：________________ （学院代盖） 年 月 日

MEG Source Imaging Algorithm for Finding Deeper Epileptogenic Zone

Yegang Hu[1,2], Yicong Lin[3], Baoshan Yang[1,2], Guangrui Tang[1,2], Yuping Wang[3], and Jicong Zhang[1,2](✉)

[1] School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China
{huyegang,bshyang,tangguangrui,jicongzhang}@buaa.edu.cn
[2] Beijing Advanced Innovation Center for Big Data-Based Precision Medicine, Beihang University, Beijing 100191, China
[3] Department of Neurology, Xuanwu Hospital, Capital Medical University, Beijing 100053, China
Linyc_1@163.com, wangyuping01@sina.cn

Abstract. In recent years, magnetoencephalography (MEG) has played a prominent role on neocortical epilepsy preoperative evaluation. However, its clinical utility with locating deeper sources may be more challenging such as the mesial temporal structures. We proposed a new source imaging algorithm for finding the epileptogenic zone in mesial temporal lobe epilepsy (mTLE). Since the localization results using the Elekta MEG method are very sensitive to some MEG noises, the source modeling was modified by spatial filtering in wavelet domain and cortex constraint. Two surgical patients randomly selected with medically refractory mTLE, which were diagnosed based on a comprehensive preoperative evaluation, had been studied in this manuscript. The localization results using proposed method on individual MRI showed that the deeper regions had been exactly found in the mesial temporal lobe. Yet, the results using the Elekta Neuromag Software only appeared in the lateral temporal lobe. Thus, the proposed algorithm maybe become an effective method in detecting deeper epileptogenic zone.

Keywords: Epileptogenic zone · Magnetoencephalography · Magnetic source imaging · Mesial temporal lobe epilepsy

1 Introduction

MEG is a neuroimaging modality that captures neural activity with high spatiotemporal resolution and minor signal deterioration from the skull and scalp [1–3]. In addition, MEG is a noninvasive and worthful tool for improving patient management in the evaluation of epilepsy and pre-surgical spike mapping for epilepsy surgery, which can help delineate the epileptogenic zone in three dimensions using magnetic source imaging (MSI) techniques [4–6].

MTLE plays an important role in pharmacoresistant or refractory epilepsy, and represents one of the most common forms of focal epilepsy [7]. Thus, mTLE is

M. Fei et al. (Eds.): LSMS/ICSEE 2017, Part I, CCIS 761, pp. 536–544, 2017.
DOI: 10.1007/978-981-10-6370-1_53

considered to be one of the most important categories of the symptomatic focal or localization-related epilepsies in epileptology, and its pathophysiological substrate is usually hippocampal sclerosis (HS) [8], which is the most common structural abnormality in human epilepsy [9]. Around two thirds of patients with temporal lobe epilepsy could achieve seizure freedom via resective epilepsy surgery, and MEG examination results become a key role in preoperative evaluation with epileptogenic zone and in guiding surgical placement of intracranial electrodes [10, 11].

Some researchers have given the view that MSI methods seem to be effective and helpful for finding the epileptic foci in neocortical epilepsy [12, 13]. Nevertheless, its ability about detecting deep sources such as those in mesial temporal lobe remains in question [14–16]. Although the magnetometer has been considered for spike detection in patients with mesial temporal epileptic focus [17], the clinical utility of MEG has not been completely accepted by consensus in preoperative evaluation with epileptogenic foci in deep regions [18]. Thus, a technical challenge is whether signals from deep sources could be well detected and correctly located using MEG device and MSI techniques.

In this manuscript, two patients randomly selected with focal epilepsy had been diagnosed as medically refractory mTLE according to a comprehensive preoperative evaluation, and almost all of the MEG localization results using the Elekta Neuromag Software method [19] appeared in the lateral temporal lobe. Of note, the Elekta Neuromag method for MEG localization is more stable than the other magnetic source imaging methods in clinical epilepsy preoperative evaluation [20–22]. Since the Elekta Neuromag method applied a snapshot of the MEG recordings under the time domain, the localization results generated by this method can be sensitive to some MEG noises. Herein we proposed a new method and applied it to the MEG recordings, which is characterized by the spatial filtering in wavelet domain and the cortex constraint.

2 Deeper Epileptogenic Zone Localization Algorithm

2.1 Data Preprocessing and Artifact Rejection

In this manuscript, three primary toolboxes including Matlab R2014a (The MathWorks Inc), SPM8 [23], and FieldTrip [24] were used jointly for MEG data analysis. The MEG signal with continuous data, which would not be divided into many segments, was filtered by a band-pass filter of 0.5–60 Hz, notch-filtered at 50 Hz, and detrended via removing the linear trend from the data. Then, the MEG channels including noises were detected by the module of manual artifact rejection, and the bad channels were repaired automatically using spline interpolation algorithm. To improve the quality of MEG recordings signals, the independent component analysis (ICA) and principal component analysis (PCA) were used for removing the artifacts related to hearbeats, muscles and eye blinks. We hoped that the interested signal containing spike waves was very clean.

2.2 Source Localization Algorithm

Two experienced clinical epileptologists visually marked epileptic spikes respectively in MEG signals after the previous step and ruled out drowsiness. Then, the individual anatomical magnetic resonance images (MRI; T1-weighted) and the digitised head shapes were co-registered to the MEG coordinate system using anatomical landmarks via an iterative closest point (ICP) algorithm [25]. Then, the detailed procedure of inverse solution would be addressed as follows.

For the preprocessed signal matrix $\mathbf{X} = [X_1, X_2, \ldots, X_q]$, which is acquired from MEG sensors, the inverse solution model is given as

$$\mathbf{X} = \mathbf{GW} + \boldsymbol{\varepsilon} \tag{1}$$

where X_i is an $N \times 1$ vector of the MEG measurements at i-th time point, N is the number of MEG sensors, $\mathbf{G}$ is the $N \times m$ (lead-field) gain matrix, m denotes the number of unknown dipole moment parameters, $\mathbf{W}$ is an $m \times q$ dipole moment matrix for given time series, and $\boldsymbol{\varepsilon}$ denotes the $N \times q$ noise matrix. Then the original observed signal would be transformed into a novel space for representing the intrinsic features from time domain to transform domain. The transformed procedure is expressed as

$$\Phi\colon \mathbf{X} \mapsto \mathbf{D} \tag{2}$$

where Φ is a Haar Wavelet transform function, $\mathbf{D}$ denotes the transformed data in novel space. Then, we employ an optimization algorithm of regularization minimizing the interference (rMinInf) [26] for passing the activity at position $\boldsymbol{r} = \boldsymbol{r}_0$ with unit gain, while inhibiting contributions from all other sources. The mathematical formulation is

$$\min_{\mathbf{A}} \left[E(\|\mathbf{AD}\|^2) + \alpha\|\mathbf{A}\|^2\right] \quad with \;\; \mathbf{AG}(r_0) = 1 \tag{3}$$

where $E(\cdot)$ denotes the expectation value function and α is the regularization coefficient. The optimal solution can be computed by minimizing the corresponding Lagrange function as

$$\mathbf{A}(\mathbf{r}) = \left(\mathbf{G}^T(\mathbf{r})(\mathbf{C} + \alpha\mathbf{I})^{-1}\mathbf{G}(\mathbf{r})\right)^{-1}(\mathbf{C} + \alpha\mathbf{I})^{-1}\mathbf{G}(\mathbf{r}) \tag{4}$$

where $\mathbf{A}(\mathbf{r})$ indicates the projection matrix at the grid location $\mathbf{r}$, T denotes matrix or vector transpose and $\mathbf{C}$ is the covariance matrix of random variables based on row vectors of the transformed domain matrix $\mathbf{D}$. Besides, the power value at each grid point, which can also be seen as the dipole moment, would be expressed as

$$\mathrm{pow}(\mathbf{r}) = \lambda_1\left(\mathbf{A}(\mathbf{r})\mathbf{C}\mathbf{A}(\mathbf{r})^{*T}\right) \tag{5}$$

where $\mathrm{pow}(\mathbf{r})$ indicates the power value at the grid location $\mathbf{r}$ and $\lambda_1(\cdot)$ denotes the maximum eigenvalue of the expression in braces. In fact, a similar approach has been attempted to find the epileptogenic zone based on MEG, and has achieved some preliminary results in an earlier study [27]. However, it was designed only for finding epileptogenic zone in neocortical epilepsy, and has not drawn much attention in clinical application.

Thus, the new procedure is summarized into an algorithm as follows. It is assumed that data preprocessing and artifact rejection have been accomplished for the MEG data and individual MRI of all the patients.

Proposed algorithm: Deeper epileptogenic zone localization procedure.

Forward solution:

1. Construct the volume conduction model **V** based on a single shell approximation under the cortex constraint.
2. Calculate the lead field matrices **G** under the cortex constraint.
3. Denote the lead field matrix $\mathbf{G}_i$ corresponding to the i-th grid point.

MEG data space transformation:

1. Pick out the k-th data segment matrix $\mathbf{X}^k$ containing spike.
2. Transform the data matrix $\mathbf{X}^k$ into wavelet domain $\mathbf{D}^k$ using the equation (2).

Inverse solution:

1. Compute the covariance matrix $\mathbf{C}^k$ of the matrix $\mathbf{D}^k$.
2. Obtain the optimized projection matrix $\mathbf{A}^k(\mathbf{r})$ at the grid location **r** based on the equation (4).
3. Calculate the power value $pow^k(\mathbf{r})$ at the grid location **r** via the equation (5).

Localization results display:

1. Select those grid points corresponding to the larger power values.
2. Visualize the result on the individual MRI using FieldTrip toolbox.

Feasibility of the above algorithm will be demonstrated by experimental results in the next section.

3 Experimental Results

3.1 Patients and Data Description

For describing the preliminary effectiveness of proposed algorithm, we adopted two patients randomly with medically refractory unilateral mTLE retrospectively. Mesial TLE was diagnosed based on a comprehensive preoperative evaluation, including seizure history and semiology, neurologic examination, 3 T MR imaging, scalp electroencephalography, invasive electroencephalography and pathology. Two patients had already undergone a standard clinical presurgical evaluation including clinical seizure semiology, long-term video-EEG monitoring, high-resolution MRI, MEG as well as neuropsychological testing. According to all of these examination results, the preoperative assessment conclusion was given by Beijing epilepsy center expert group members. And then, two patients had also accomplished anterior temporal lobectomy [28] for focal epilepsy at Xuanwu Hospital Capital Medical University (XWHCMU) on June 2013, which included three years postoperative follow-up. The results showed that two patients were free of disabling seizures (Engel class IA) after surgery. The study was performed under a protocol approved by the medical ethics committee of the XWHCMU Committee.

MEG Acquisition. The MEG recordings were acquired inside a magnetically shielded room by the 306 channels in total with a helmet-shaped whole-head system (Vector-View, Elekta Neuromag Oy, Finland), comprising 102 locations at triplets including one magnetometer and two orthogonal planar gradiometers. For mTLE patients, continuous data were recorded at a sampling rate of 1000 Hz for the MEG signal, and the electrocardiography data was recorded simultaneously. Each recording consisted of six 10-min epochs while they were lying in a supine position with eyes closed and resting-state. A three-dimensional digitizer, which was the Polhemus™ system (Colchester, NH, USA), was used to determine the location based on anatomical fiducial points (nasion, bilateral preauricular points) for the following MRI-MEG co-registration. Through checking the uniform distribution of points as far as possible covering the whole scalp, the head shape of each patient was ascertained ensuring that the head of patient cannot be moved in the whole procedure.

3.2 Deep Source Localization Results

Clinical characteristics of the two patients were listed in Table 1, and the two epilepsy patients were judged as mesial Temporal Lobe (TL) origination based on preoperative evaluation and postoperative follow-up. From the clinical experience, the localization results could be found in the mesial TL region, and may also be found in lateral or extra TL region, because the discharge sources may spread from one location to another during a short time. Then, MEG source imaging results would be shown from coronal and sagittal views as follows.

Table 1. Clinical characteristics of the two patients and localization results.

Clinical index	Patient 1 (Results)	Patient 2 (Results)
MRI	Hyper T2 in right hippocampal	Normal
Preoperative evaluation	**mesial temporal lobe origination**	**mesial temporal lobe origination**
Surgical procedure	right anterior temporal lobectomy (include hippocampal)	right anterior temporal lobectomy (include hippocampal)
Postoperative follow-up	Seizure Free (Engel class IA)	Seizure Free (Engel class IA)
MEG (Elekta Neuromag)	Lateral temporal lobe (right)	Lateral temporal lobe (right)
MEG (Proposed method)	**Mesial temporal lobe(right)**	**Mesial temporal lobe(right)**

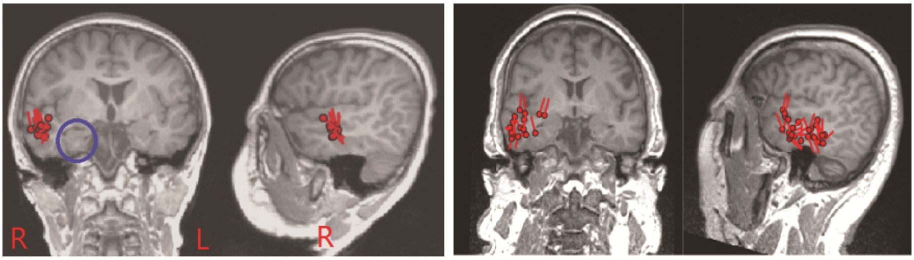

Fig. 1. Magnetic source imaging results based on Elekta Neuromag Software. (a) The localization results with the 1st patient displayed on individual MRI from coronal and sagittal views, wherein the hippocampal region was denoted by blue circle on coronal view. (b) The localization results with the 2nd patient displayed on individual MRI from coronal and sagittal views. (Color figure online)

First, Fig. 1 gave the localization results using Elekta Neuromag Software, which were reviewed by clinical MEG neurologists, and these results obviously showed that almost all of the dipoles were displayed in lateral TL region. Second, the localization results using proposed scheme were displayed on individual MRI of epilepsy patient. For clearly observing the deeper regions around hippocampal, we exhibited a figure

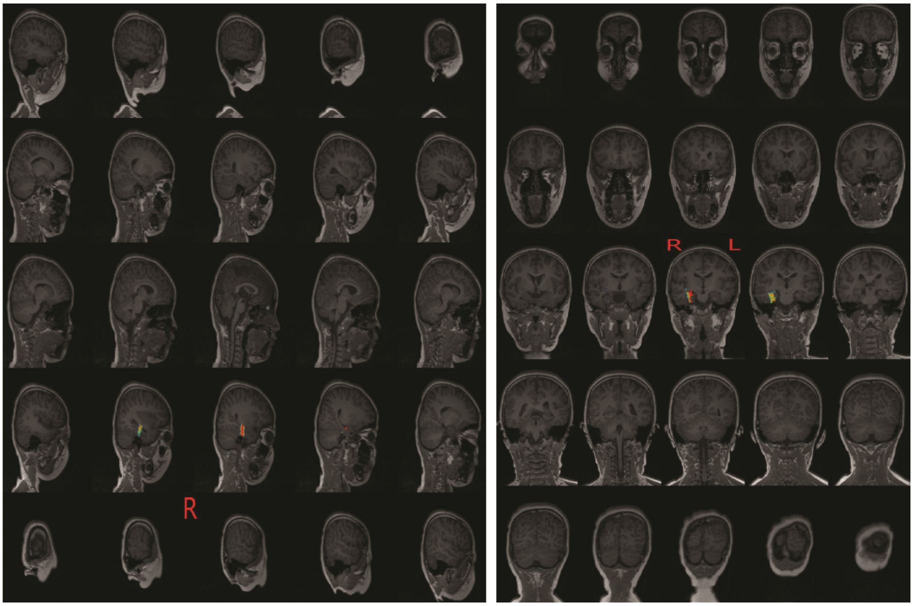

Fig. 2. MSI results of the 1st patient displayed on individual MRI using this paper method from coronal and sagittal views respectively.

including a total of 25 slices, 5 rows by 5 columns, from coronal and sagittal views respectively. Figure 2 showed that the localization results had appeared in the right hippocampal region, thus this patient could be judged as mesial TL origination. Analogously, the second patient could also be judged as mesial TL origination from Fig. 3. Of note, MRI examination results showed that the signal of hippocampus region was normal for the second patient, and it perhaps illustrate that MRI examination often generates false negative results. In addition, we observed that the source activity regions were also located in anterior TL based on MEG using the two methods.

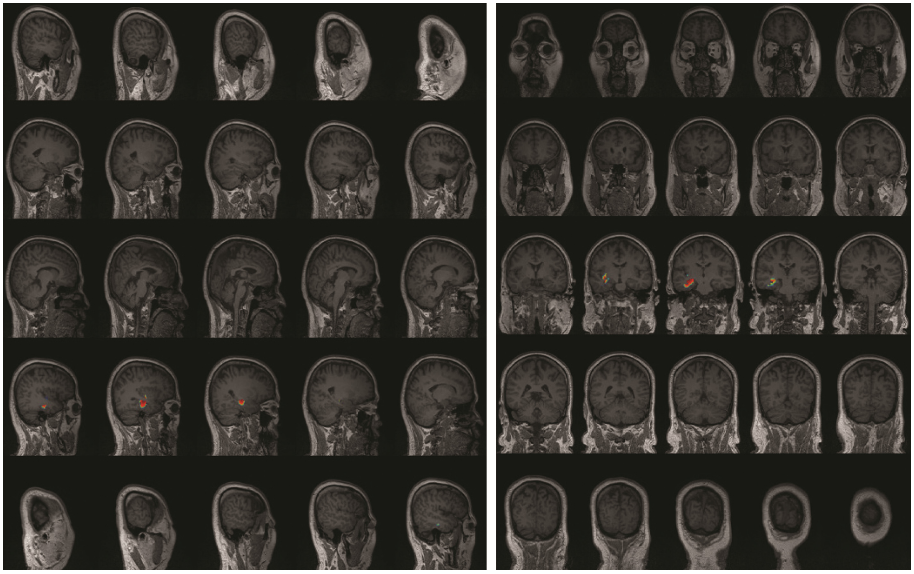

Fig. 3. MSI results of the 2nd patient displayed on individual MRI using this paper method from coronal and sagittal views respectively.

In a word, the proposed method results were almost consistent with the clinical comprehensive preoperative evaluation, surgical outcome and postoperative follow-ups (See Table 1). Compared with the Elekta Neuromag method, the proposed algorithm has obviously prominent for detecting the discharge sources in mesial TL region with the two epilepsy patients. Thus, MEG source imaging plays an important role for epileptogenic zone localization in preoperative evaluation of epilepsy.

4 Conclusion and Discussion

In conclusion, we designed a new MSI algorithm by combining a kind of spatial filtering in the wavelet domain and the cortex constraint to identify the deep epileptogenic zone in mTLE patients detected from preoperative MEG recordings. The proposed method results seem to be more consistent with the multi-modality neuroimages, clinical characteristics, and postoperative follow-ups of those patients. Compared with the Elekta

Neuromag method, this paper method is capable of detecting deep sources in the brain. Thus, it may help increase the clinical utility of MEG in preoperative evaluation with epileptogenic foci in deep brain regions. Yet, the proposed method only provided preliminary framework on finding deeper epileptogenic zone, because of the limited number of cases. In future, to generalize the proposed method in clinical application, more number of patients will be adopted for verifying this method.

Acknowledgments. This work was supported by National Key Research and Development program of the Ministry of Science and Technology (grant number 2016YFF0201002), the Natural Science Foundation of China (grant numbers 61301005 and 61572055), the Natural Science Project of National Statistical Bureau (2014LY088), the project of Brain Functional Disease and Neuromodulation of Beijing Key Laboratory, 'Thousands of People Plan' Workstation between Beihang University and Jiangsu Yuwell Medical Equipment & Supply Co. Ltd.

References

1. Nissen, I.A., Stam, C.J., Citroen, J., Reijneveldb, J.C., Hillebranda, A.: Preoperative evaluation using magnetoencephalography: experience in 382 epilepsy patients. Epilepsy Res. **124**, 23–33 (2016)
2. Barnes, G.R., Hillebrand, A.: Statistical flattening of MEG beamformer images. Hum. Brain Mapp. **18**, 1–12 (2003)
3. Zumer, J.M., Attias, H.T., Sekihara, K., Nagarajan, S.S.: A probabilistic algorithm integrating source localization and noise suppression for MEG and EEG data. Neuroimage **37**, 102–115 (2007)
4. Wu, J.Y., et al.: Magnetic source imaging localizes epileptogenic zone in children with tuberous sclerosis complex. Neurology **66**, 1270–1272 (2006)
5. Nissen, I.A., et al.: Identifying the epileptogenic zone in interictal resting-state MEG source-space networks. Epilepsia **58**, 137–148 (2017)
6. Hillebrand, A., Singh, K.D., Holliday, I.E., Furlong, P.L., Barnes, G.R.: A new approach to neuroimaging with magnetoencephalography. Hum. Brain Mapp. **25**, 199–211 (2005)
7. Engel, J.: Introduction to temporal lobe epilepsy. Epilepsy Res. **26**, 141–150 (1996)
8. Engel, J.: Mesial temporal lobe epilepsy: what have we learned? Neuroscientist **7**, 340–352 (2001)
9. Engel, J.: Recent advances in surgical treatment of temporal lobe epilepsy. Acta Neurol. Scand. **86**(S140), 71–80 (1992)
10. Sutherling, W.W., et al.: Influence of magnetic source imaging for planning intracranial EEG in epilepsy. Neurology **71**, 990–996 (2008)
11. Murakami, H., et al.: Correlating magnetoencephalography to stereo-electroencephalography in patients undergoing epilepsy surgery. Brain **139**, 2935–2947 (2016)
12. Bast, T., et al.: EEG and MEG source analysis of single and averaged interictal spikes reveals intrinsic epileptogenicity in focal cortical dysplasia. Epilepsia **45**, 621–631 (2004)
13. Wennberg, R., Cheyne, D.: Reliability of MEG source imaging of anterior temporal spikes: analysis of an intracranially characterized spike focus. Clin. Neurophysiol. **125**, 903–918 (2014)
14. Leijten, F.S.S., et al.: High-resolution source imaging in mesiotemporal lobe epilepsy: a comparison between MEG and simultaneous EEG. J. Clin. Neurophysiol. **20**, 227–238 (2003)

15. Shigeto, H., et al.: Feasibility and limitations of magnetoencephalographic detection of epileptic discharges: simultaneous recording of magnetic fields and electrocorticography. Neurol. Res. **24**, 531–536 (2002)
16. Wennberg, R., Valianteb, T., Cheynec, D.: EEG and MEG in mesial temporal lobe epilepsy: where do the spikes really come from? Clin. Neurophysiol. **122**, 1295–1313 (2011)
17. Enatsu, R., et al.: Usefulness of MEG magnetometer for spike detection in patients with mesial temporal epileptic focus. Neuroimage **41**, 1206–1219 (2008)
18. Bagić, A., Ebersole, J.S.: Does MEG/MSI dipole variability mean unreliability? Clin. Neurophysiol. **126**, 209–211 (2015)
19. Elekta Neuromag Oy: The MEG signal processor (graph) users guide and reference manual. http://www.martinos.org/meg/Neuromag-manuals.php. Accessed 13 June 2017
20. Oishi, M., et al.: Single and multiple clusters of magnetoencephalographic dipoles in neocortical epilepsy: significance in characterizing the epileptogenic zone. Epilepsia **47**, 355–364 (2006)
21. Knake, S., et al.: The value of multichannel MEG and EEG in the presurgical evaluation of 70 epilepsy patients. Epilepsy Res. **69**, 80–86 (2006)
22. Medvedovsky, M., et al.: Sensitivity and specificity of seizure-onset zone estimation by ictal magnetoencephalography. Epilepsia **53**, 1649–1657 (2012)
23. Litvak, V., et al.: EEG and MEG data analysis in SPM8. Comput. Intell. Neurosci. **2011**, 852961 (2011)
24. Oostenveld, R., Fries, P., Maris, E., Schoffelen, J.M.: FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. Comput. Intell. Neurosci. **2011**, 156869 (2011)
25. Besl, P.J., McKay, N.D.: A method for registration of 3D shapes. IEEE T Pattern Anal. **14**, 239–254 (1992)
26. Gross, J., Ioannides, A.A.: Linear transformations of data space in MEG. Phys. Med. Biol. **44**, 2081–2097 (1999)
27. Heers, M., et al.: Frequency domain beamforming of magnetoencephalographic beta band activity in epilepsy patients with focal cortical dysplasia. Epilepsy Res. **108**, 1195–1203 (2014)
28. Schaller, K., Cabrilo, I.: Anterior temporal lobectomy. Acta Neurochir. **158**, 161–166 (2016)

Manuscript Details

Manuscript number	JOLT_2018_387_R1
Title	Low-Rank Matrix Recovery for Source Imaging with Magnetoencephalography
Article type	Research Paper

Abstract

Source imaging with magnetoencephalography (MEG) provides good spatial accuracy for shallow sources and has been successfully applied for the study of brain cognition and the diagnosis of brain diseases. Yet, its utility for locating deep sources is unclear and remains a technical challenge. In this study, we proposed a new source imaging method for the assessment of brain activity in deep locations. A MEG sensor array with 306 channels was represented as a low-rank matrix plus sparse noise. The low-rank matrix was then used to estimate the source model with minimum variance beamforming. Simulations of a realistic head model indicated that the proposed method was effective. Our method was further verified in 10 patients with temporal lobe epilepsy, wherein the imaging results were consistent with clinical findings.

Keywords	Beamforming; epileptogenic zone; low-rank matrix recovery; magnetoencephalography; source imaging.
Manuscript category	Optical information processing and systems

Corresponding Author	Jicong Zhang
Corresponding Author's Institution	School of Biological Science and Medical Engineering, Beihang University
Order of Authors	Yegang Hu, Yuping Wang, Jicong Zhang
Suggested reviewers	Guangxu Li, Huimin Lu, Xin Jin

Submission Files Included in this PDF

File Name [File Type]

Coverletter.docx [Cover Letter]

Response Reviewers.docx [Response to Reviewers]

Highlights.docx [Highlights]

Low-Rank Matrix Recovery for Source Imaging with Magnetoencephalography-v1.docx [Manuscript File]

Low-Rank Matrix Recovery for Source Imaging with Magnetoencephalography

Yegang Hu[a,b,c], Yuping Wang[d,e] , Jicong Zhang[a,b,c,*]

[a] School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China
[b] Beijing Advanced Innovation Centre for Big Data-Based Precision Medicine, Beihang University, Beijing 100191, China
[c] Beijing Advanced Innovation Centre for Biomedical Engineering, Beihang University, Beijing 100191, China
[d] Department of Neurology, Xuanwu Hospital, Capital Medical University, Beijing 100053, China
[e] Beijing Key Laboratory of Brain Functional Disease and Neuromodulation, Beijing 100053, China
[*] Corresponding author: jicongzhang@buaa.edu.cn

Abstract. Source imaging with magnetoencephalography (MEG) provides good spatial accuracy for shallow sources and has been successfully applied for the study of brain cognition and the diagnosis of brain diseases. Yet, its utility for locating deep sources is unclear and remains a technical challenge. In this study, we proposed a new source imaging method for the assessment of brain activity in deep locations. A MEG sensor array with 306 channels was represented as a low-rank matrix plus sparse noise. The low-rank matrix was then used to estimate the source model with minimum variance beamforming. Simulations of a realistic head model indicated that the proposed method was effective. Our method was further verified in 10 patients with temporal lobe epilepsy, wherein the imaging results were consistent with clinical findings.

Keywords: beamforming, epileptogenic zone, low-rank matrix recovery, magnetoencephalography, source imaging.

1 Introduction

Magnetoencephalography (MEG) captures superficial neural activities with high spatiotemporal resolution in a manner that is less affected by the skull and scalp than electroencephalography [1][2]. In recent years, MEG has played an important role in the field of neuroimaging and has demonstrated particular utility for the

sensors

MDPI

Article

Deep Source Localization with Magnetoencephalography Based on Sensor Array Decomposition and Beamforming

Yegang Hu [1,2,3], Yicong Lin [4,5], Baoshan Yang [1,2,3], Guangrui Tang [1,2,3], Tao Liu [1,2,3], Yuping Wang [4,5] and Jicong Zhang [1,2,3,*]

1. School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China; huyegang0630@126.com (Y.H.); bshyang@buaa.edu.cn (B.Y.); tangguangrui@buaa.edu.cn (G.T.); tao.liu@buaa.edu.cn (T.L.)
2. Beijing Advanced Innovation Center for Biomedical Engineering, Beihang University, Beijing 100191, China
3. Beijing Advanced Innovation Center for Big Data-Based Precision Medicine, Beihang University, Beijing 100191, China
4. Department of Neurology, Xuanwu Hospital, Capital Medical University, Beijing 100053, China; liny@xwhosp.org (Y.L.); wangyuping@xwhosp.org (Y.W.)
5. Brain Functional Disease and Neuromodulation of Beijing Key Laboratory, Beijing 100053, China

* Correspondence: jicongzhang@buaa.edu.cn; Tel.: +86-135-2007-2136

Received: 17 May 2017; Accepted: 2 August 2017; Published: 11 August 2017

Abstract: In recent years, the source localization technique of magnetoencephalography (MEG) has played a prominent role in cognitive neuroscience and in the diagnosis and treatment of neurological and psychological disorders. However, locating deep brain activities such as in the mesial temporal structures, especially in preoperative evaluation of epilepsy patients, may be more challenging. In this work we have proposed a modified beamforming approach for finding deep sources. First, an iterative spatiotemporal signal decomposition was employed for reconstructing the sensor arrays, which could characterize the intrinsic discriminant features for interpreting sensor signals. Next, a sensor covariance matrix was estimated under the new reconstructed space. Then, a well-known vector beamforming approach, which was a linearly constraint minimum variance (LCMV) approach, was applied to compute the solution for the inverse problem. It can be shown that the proposed source localization approach can give better localization accuracy than two other commonly-used beamforming methods (LCMV, MUSIC) in simulated MEG measurements generated with deep sources. Further, we applied the proposed approach to real MEG data recorded from ten patients with medically-refractory mesial temporal lobe epilepsy (mTLE) for finding epileptogenic zone(s), and there was a good agreement between those findings by the proposed approach and the clinical comprehensive results.

Keywords: magnetoencephalography; deep source localization; iterative matrix decomposition; beamforming; epileptogenic zone; mesial temporal lobe epilepsy

1. Introduction

MEG is a functional neuroimaging technique that captures neural activity with high spatiotemporal resolution and minor signal deterioration from the skull and scalp [1–4]. Since different source activities can generate an identical magnetic field distribution at the MEG sensor arrays, source localization techniques become an essential step for finding real sources by modeling the inverse solution in one assumption. At present, many studies have shown that MEG source localization methods seem to be effective and helpful for detecting surface sources, especially for finding the epileptogenic zone of neocortical epilepsy [5,6]. Meanwhile, deep source detection plays a more and