INVERSE SOLUTION FOR SINGLE SLEEP SPINDLES PARAMETERIZED BY MULTICHANNEL MATCHING PURSUIT

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Abstract: The aim of presented study is to relate temporal oscillatory activity in sleep EEG (sleep spindles) to anatomical locations of their cerebral generators. Such an automatic method was proposed in [1] and current work is solely based on it. The goal is achieved by sequential application of two algorithms: multichannel matching pursuit (mmp) with discrete Gabor dictionary, followed by a maximum smoothness EEG inverse solution (LORETA).

Introduction

Although new methods are available for brain diagnosis EEG still has much to offer. Due to its high temporal resolution, it can be directly related to brain functional (dynamical) state. It is non-invasive and non-disturbing and therefore adequate for an in vivo study of the brain dynamics in a natural environment. EEG consists of measurements of the electric potential on the scalp, which is produced by synchronous and spatially coherent electrical activity of masses of neurons in the brain. The relationship between these electrical sources (electric current density) and the measured voltages can be established from the Maxwell equations, appropriate boundary conditions and assumptions on the properties of the volume conductor.

In this work we use above features to study phenomena arising in sleep analysis. In normal subject during stage 2 of non REM sleep the EEG signal shows a wave with duration $0.5-2sec$ and frequency $12-14Hz$ [2] [3]. This is an "EEG image" of the phenomena described as a sleep spindle. Further investigation leads to dividing sleep spindles into two groups: fast with frequency around $14Hz$ and slow with frequency around $12Hz$. Also it was found that fast sleep spindles have higher spectral power in central and parietal electrodes, and slow in frontal electrodes [4] [5]. On the other hand sleep spindles can be traced down by the in-vivo recordings to thalamus, suggesting they are a reflection of thalamocortical events [6] [5]. Current work will focus on neuronal generators or sources (in this work: smoothest primary current distribution $\vec{J}$) of sleep spindles. The proposed methodology is based on a sequential use of two algorithms:

- multichannel matching pursuit (mmp) with dictionary of gabor functions [7]. It decomposes the multichannel EEG signal into a sum of one-dimensional (1d) gabor functions (parameterized by frequency, time and duration) multiplied by inner products between this gabor function and the EEG signal in every channel (spatial signature). From such a decomposition it is easy to filter out fast and slow EEG images of sleep spindles (gabor function with duration $0.5-2sec$ and frequency around $12Hz$ or $14Hz$),
- a version of LORETA inverse solution [8] from the spatial signature of every atom representing 'EEG image' of sleep spindles. Loreta gives the smoothest electric current density in the brain and we use a solution further constrained to the gray matter of an average brain [9].

Methods

Background

Let us recall the assumptions used in this study (for details see [10] [11]). EEG measures voltage difference $V(\vec{r},t)$ between scalar potential $\Phi(\vec{r},t)$ at a given spatiotemporal position ($\vec{r}$ - electrode, t - time) and some reference scalar potential $\Phi_{re}(t)$ usually taken as scalar potential at some reference electrode $\vec{r}_{re}$ i.e. $\Phi_{ref}(t) = \Phi(\vec{r}_{re},t)$. The voltage $V(\vec{r},t)$ is uniquely related to primary current density $\vec{J}(\vec{r},t)$ inside the brain. This relation is stated by Maxwell equations being the basic assumptions:

- The head is modeled as consisting of three homogenous and isotropic concentric spheres Ω_i, corresponding to brain (inner), bone (middle) and scalp (outer),
- Capacitive and inductive properties of the volume conductor are not considered,
- The continuity conditions for voltages between adjacent spheres Ω_i and Ω_i are satisfied.

These assumptions allow to state a linear relation between $\vec{J}(\vec{r},t)$ and measured $V(\vec{r},t)$ which is known as the solution of the EEG forward problem. From the point of view of inverse problem (finding the primary cur-

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rent density from the measured voltages), this relation corresponds to a Fredholm integral equation of the first kind, whose kernel is the reciprocal current field $\vec{J}_{LE}$, also known as electric lead field [12] [13]

$$V(\vec{r},t) = \sum_i \int_{\Omega_i} \frac{1}{\sigma_i} \vec{J}_{LE}(\vec{r}')\vec{J}(\vec{r}',t)d^3\vec{r}' \qquad (1)$$

The analytic formulae of $\vec{J}_{LE}$ for three concentric spheres model can be found in [13].

Multichannel matching pursuit

The multichannel matching pursuit algorithm is an extension of one dimensional matching pursuit algorithm [14]. It offers a sub-optimal linear decomposition of discrete multichannel time series among nonorthogonal and redundant set (dictionary) of gabor functions (atoms) [7]. This decomposition in the matrix notation reads as:

$$\mathbf{V}_{N_e \times N_t} = \hat{\mathbf{V}}^T_{N_a \times N_e} \mathbf{G}_{N_a \times N_t} + R^{N_a+1}\mathbf{V}_{Ne \times Nt} \qquad (2)$$

where **V** is a multichannel EEG signal; the *a*-th row of matrix **G** are time samples of one-dimensional normalized discrete gabor atom (1d atom) chosen as best (in this study the one in the dictionary which gives the maximum value of the square of the sum of inner products between given atom and channels) in *a*-th iteration of mmp. The *e*-th row of *a*-th column of matrix $\hat{\mathbf{V}}$ is an inner product between best 1d atom chosen in *a*-th iteration and EEG signal in *e*-th channel, thereinafter the spatial signature for given atom. The $R^{N_a+1}\mathbf{V}$ is a residuum left after last iteration.

Inverse solution

The discrete version of relation between scalp multichannel EEG time series **V** and the primary current density time series **J** is described as a system of linear equation:

$$\mathbf{V}_{N_e \times N_t} = \mathbf{K}_{N_e \times 3N_s} \mathbf{J}_{3N_s \times N_t} + \mathbf{E}_{N_e \times N_t} \qquad (3)$$

The columns of matrix **J** correspond to thrice the number of subvolumes (voxels) elements, corresponding to the x, y and z components of the primary current density vector in each voxel of a cubic grid defined inside the brain, and rows correspond to time samples. The grid constant is *h*. The matrix **K**, linking the current density with themeasurements is called the lead field matrix. The matrix **E** is an additive random element representing unmodeled effects such as observation noise. Standard inverse problem is defined as the estimation of current density time series J from EEG voltages **V** independently for every time point (column of matrix **V**: V_t). EEG IP constitutes an ill-conditioned (sensitive to noise) and ill-posed (non-uniqueness) problem, so additional constraints are required for obtaining a unique solution. According to the constraints used, several inverse solutions has been proposed. See [15] for a review. Because lead field **K** is not dependent on time and frequency and assuming that the current density mimics the dynamics of the voltages, one can obtain an inverse problem between EEG atom series $\hat{\mathbf{V}}$ ($\mathbf{V} = \hat{\mathbf{V}}^T\mathbf{G}$) and the primary current density atom series $\hat{\mathbf{J}}$ ($\mathbf{J} = \hat{\mathbf{J}}^T\mathbf{G}$);

$$\hat{\mathbf{V}}_{N_e \times N_a} = \mathbf{K}_{N_e \times 3N_s} \hat{\mathbf{J}}_{3N_s \times N_a} + \hat{\mathbf{E}}_{N_e \times N_t} \qquad (4)$$

The equation (4) has the same form as equation (3), therefore we can use any of the known inverse solutions for the estimation of the current density $\hat{\mathbf{J}}$ series from a EEG atom series $\hat{\mathbf{V}}$ independently for every atom (columns of matrix $\hat{\mathbf{V}}$ and $\hat{\mathbf{J}}$). In this work we will assume that the inverse solution is the smoothest one and furthermore we will constrain the sources to be in the cortex (grey matter) [8], [9]

Results

An epoch of stage 2 sleep EEG (figure 1 left) was decomposed by mmp into atoms series. Sleep spindles were parameterized as gabor functions (atoms) with given duration ($0.5 - 2sec$) frequency ($11 - 15Hz$) and sum of peak to peak amplitudes across all channels exceeding ($< N_e * 5\mu V$). Two atoms conforming to the criteria of sleep spindles were found (figure 1 right). Loreta inverse solutions of corresponding topographies were found by automatic choice of the regularization parameter by minimalization of generalized cross-validation function (figures 2 and 3).

Conclusions

In this study we combine adaptive time-frequency parameterization of EEG structures and EEG source localization. In the first step we find an automatic characterization in time and frequency of sleep spindles and in the second step, the corresponding spatial sources inside the brain are found. This methodology provides a complete space-time-frequency decomposition of EEG activity of interest. Sources of the sleep spindles found in this work are consistent with previous work [3] - obtained after a visual identification of sleep spindles and a heavy post processing of the inverse solutions. In this study we also found the differential source distribution between fast and slow spindles with the analysis of only two single sleep spindles. Thus, our methodology provides of a robust source reconstruction which is at the same time characterized in time and frequency. This procedure provides an automatic parameterization of all the sleep spindles present in given recording in terms of their: time positions, lengths, frequencies and amplitudes in each channel. These parameters can be an input to inverse problem solution like LORETA.

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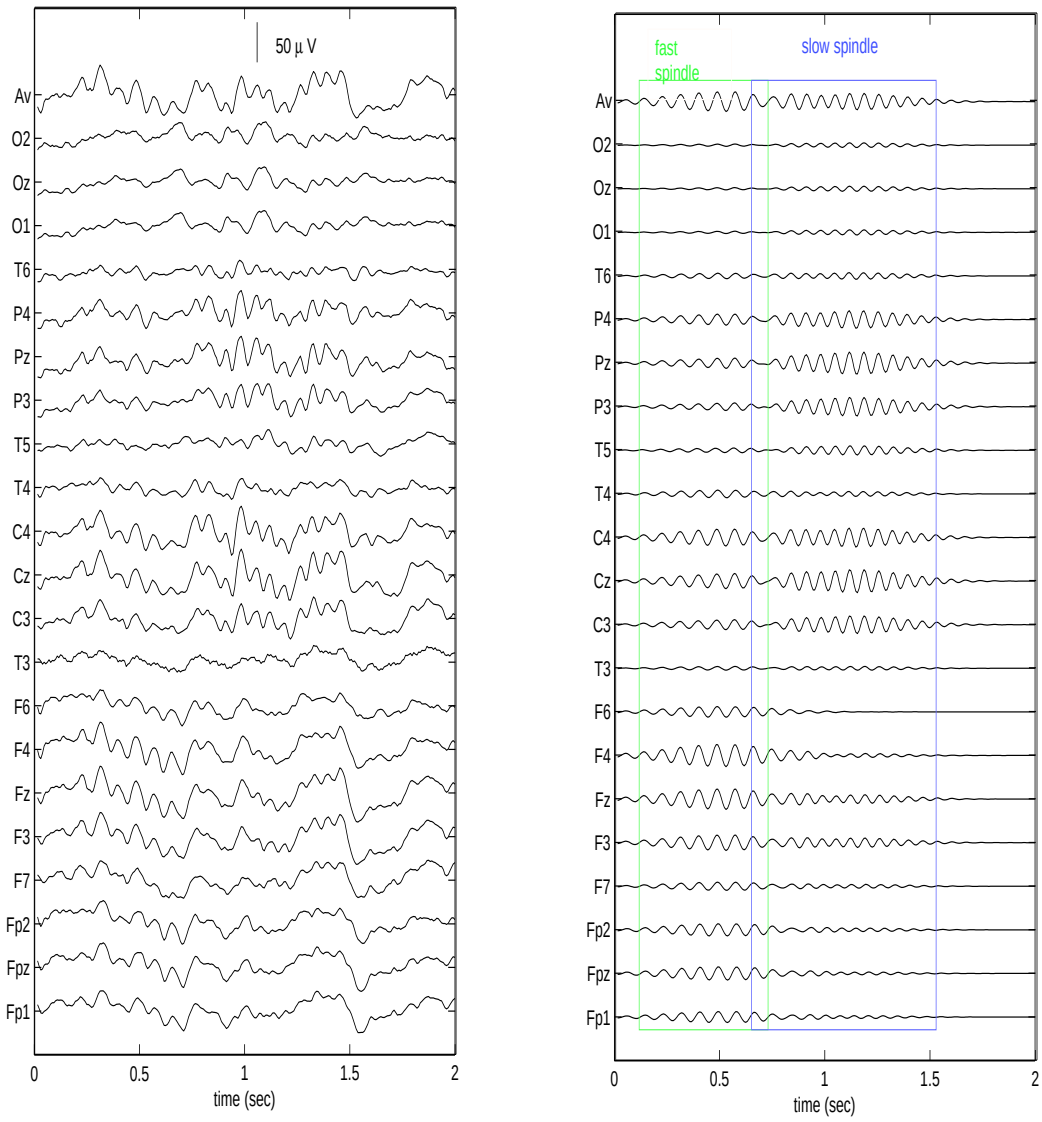

Figure 1: left: 2 s of sleep EEG from 21 standard electrodes (uppermost trace average). Upper right: time courses of two Gabor functions, conforming to the criteria of sleep spindles, fitted to the EEG presented on the left by the multichannel matching pursuit mmp. The first atom (slow spindle) is centered around 0.5*sec* and 11*Hz*. Center of the second atom (fast spindle) is around 1*sec* and 14*Hz*.

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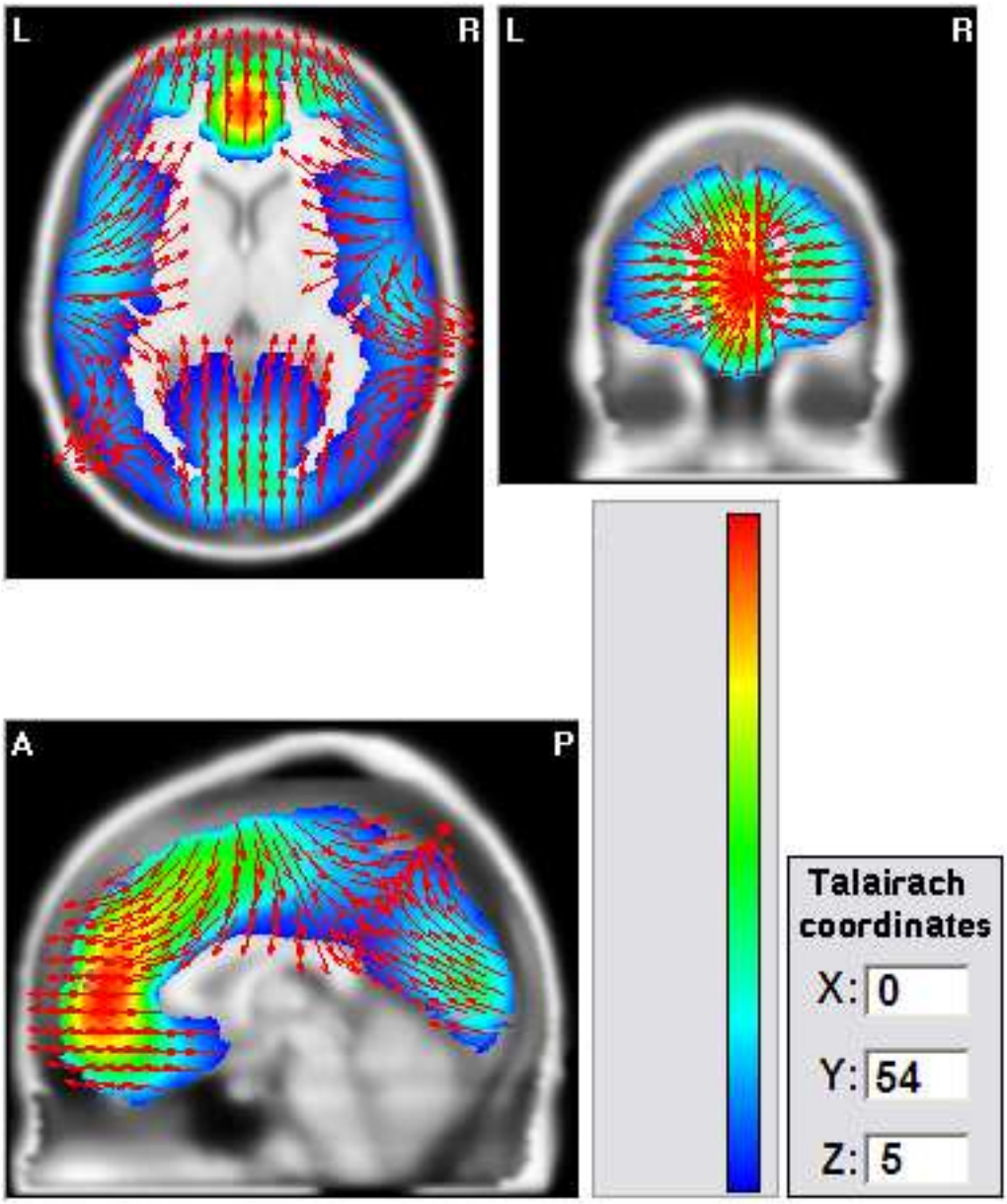

Figure 2: Primary current density amplitude and direction of the slow spindle generator, pronounced in the frontal derivations, obtained by inverse solution LORETA. Visualized by BetViewer.

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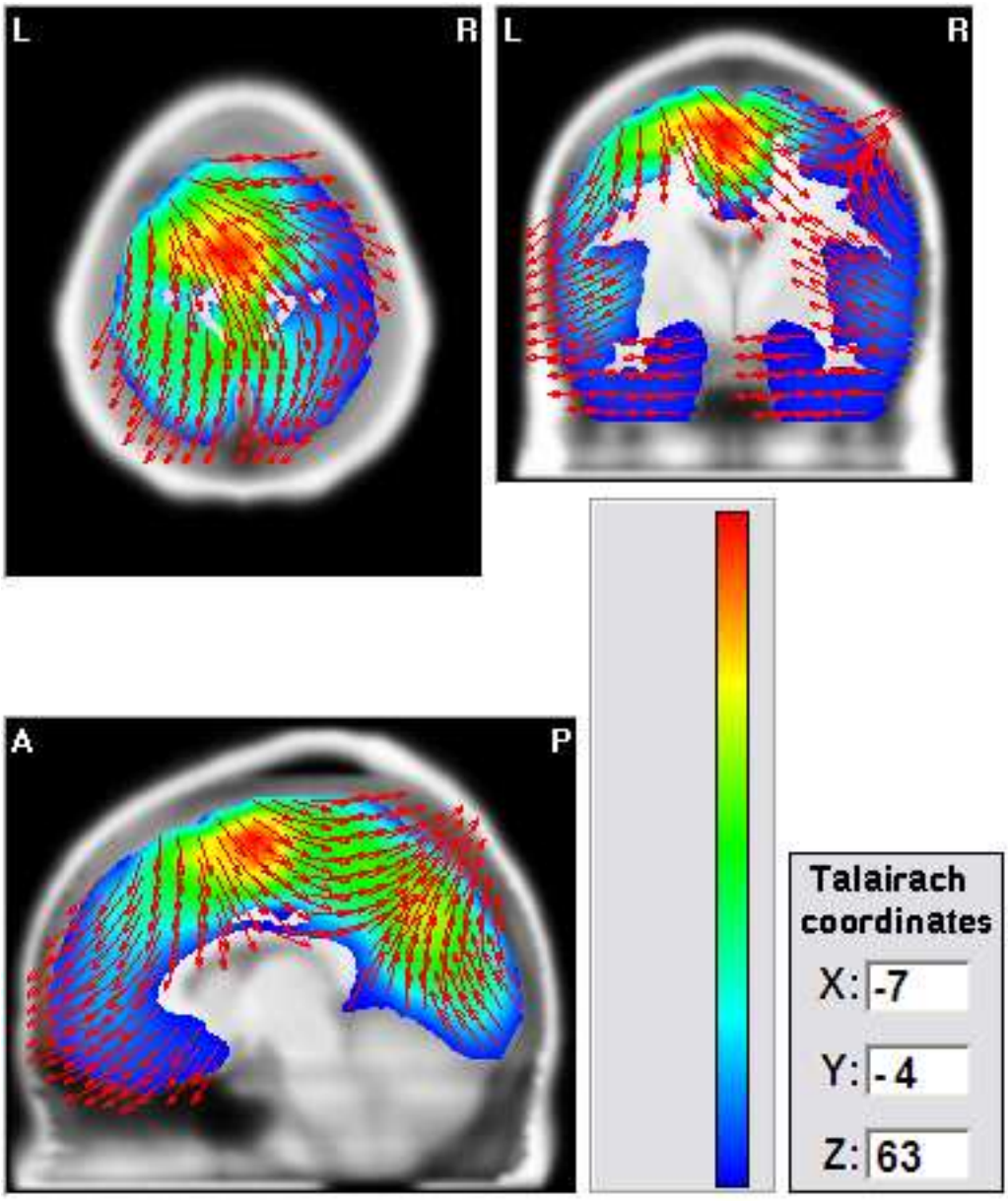

Figure 3: Primary current density amplitude and direction of the fast spindle generator, pronounced in the parietal derivations. Visualized by BetViewer.

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References

[1] DURKA P.J., MATYSIAK A., MARTINEZ MONTES E., VALDES SOSA P., and BLINOWSKA K. J. Multichannel matching pursuit and eeg inverse solutions. *Journal of Neuroscience Methods: accepted for publication*, 2005.

[2] RECHTSCHAFFEN A. and KALES A. A manual of standardized terminology, techniques and scoring system for sleep stages in human subjects.

[3] ANDERER P., KLOSCH G., GRUBER G., TRENKER E. , PASCUAL-MARQUI R.D., ZEITLHOFER J., BARBANOJ M.J. , RAPPELSBERGER P. , and SALETU B. . Low-resolution brain electromagnetic tomography revealed simultaneously active frontal and parietal sleep spindles sources in the human cortex. *Neuroscience*, 103(3).

[4] ZYGIEREWICZ J., BLINOWSKA K.J., DURKA P.J. , SZELENBERGER W., NIEMCEWICZ SZ., and ANDROSIUK W. High resolution study of sleep spindles. *Clinical Neurophysiology*, 12:2136–2147, 1999.

[5] DORAN S. The dynamic topography of individual sleep spindles. *Sleep Research Online*, 4:133–139, 2003.

[6] STERIADE M. . Basic mechanisms of sleep generation. *Neurology*, 42:9–17, 1992.

[7] GRIBONVAL R. . Piecewise linear source separation. *Proceedings SPIE*, 5207, 2003.

[8] PASCUAL-MARQUI R.D. , MICHEL C.M. , and LEHMAN D. Low resolution electromagnetic tomography:a new method to localize electrical activity in the brain. *International Journal of Psychophysiology*, 18:49–65, 1994.

[9] TRUJILLO-BARRETO N. J. , AUBERT E. , and VALDES-SOSA P.A. . Bayesian model averaging in eeg/meg imaging. *NeuroImage*, 21:1300–1319, 2004.

[10] MALMIVUO J. and PLONSEY R. . Bioelectromagnetism - principles and applications of bioelectric and biomagnetic fields. *Oxford University Press*, 1995.

[11] NUNEZ P.L. . Electric fields of the brain. *Oxford University Press*, 1981.

[12] RUSH S. and DRISCOLL D. A. . Eeg electrode sensitivity - an application of reciprocity. *IEEE Transactions on Biomedical Engineering*, 16:15–22, 1969.

[13] RIERA J. and FUENTES M.E. . Electric lead field for a piece-wise homogeneous volume conductor model of the head. *IEEE Transactions on Biomedical Engineering*, 1997.

[14] MALLAT S. and ZHANG Z. . Matching pursuit with time-frequency dictionaries. *IEEE Transactions on Signal Processing*, 41:3397–3415, 1993.

[15] PASCUAL-MARQUI, R.D. . Review of methods for solving the eeg inverse problem. *International Journal of Bioelectromagnetism*, 1:75–86, 1999.

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