MEG Beamformer Imaging of Frequency Differences

Robinson SE, Gumenyuk V, Drake CL, and Tepley N

Henry Ford Hospital, 48202 Detroit, USA

robinson@neurnis.neuro.hfh.edu

ABSTRACT

We present a new MEG functional imaging technique using a scalar linearly constrained minimum variance (LCMV) beamformer to represent differences in source power in two different frequency passbands. When mapping features of cortical oscillatory activity, the question arises as to whether each feature – for example, an alpha (8 – 11 Hz) versus sigma or sleep spindle (12 – 15 Hz) – is unique to a particular cortical location or instead represents a dynamic feature that depends upon the brain state. This analysis was applied to sleep study MEG recordings from four normal subjects. A consistent source distribution pattern was observed during transition from awake to sleep stages 1 and 2. This demonstrates that imaging differences between frequency bands can reveal subtle patterns that are not obvious using other MEG analysis methods.

KEYWORDS: MEG, LCMV beamformer, brain rhythms, sleep study, functional imaging

INTRODUCTION

The LCMV beamformer has been widely used for event-related MEG imaging of either time-locked changes in power (for a specified frequency band) [1] or phase-locked activity represented by averaged signals [2]. These analyses are appropriate to sensory, motor, and cognitive studies, but are unrevealing for observing transitions in spontaneous brain activity. The beamformer, in its current derivations, estimates the uncorrelated fraction of the source activity. This is because a current dipole model is used as the beamformer constraint. Correlated activity due to more than one dipole source is attenuated. The rhythms observed in spontaneous MEG or EEG are the result of superposition of highly correlated distributed sources. Functional imaging using the scalar LCMV beamformer reveals only the uncorrelated focal source activity.

Beamformer images comparing source power during wake versus sleep stages 1 and 2 show no coherent source pattern. Source power during the wake stage is greater than that during sleep. Also, there is a general shift toward lower frequency activity in sleep. Beamformer images comparing wake with sleep stages after subdividing the MEG data into frequency bands for delta, theta, alpha, beta, and gamma bands is similarly unrevealing. Beamformer comparison of alpha, sigma spindles, and non-spindle activity after parsing the MEG data into segments containing each feature shows no source distribution pattern to distinguish these features.

The reason for the seemingly chaotic functional image patterns is that sources that are engaged in any single feature such as sigma activity are also engaged, at other times in generating the other rhythms. This is revealed by applying the beamformer to display the source waveform for a particular location [3].

The generators of alpha and sigma spindles appear to be a dynamic feature of cortical activity, and not a function that is specific to any given site. This suggests that some insight into the rhythmic patterns associated with the wake and sleep stages may be revealed by comparing activity in two frequency bands. This analysis and some associated results are the subject of this report.

METHODS

The mathematical derivation of the scalar LCMV beamformer for MEG has been treated in detail, elsewhere [4,5]. Multiple spontaneous data recordings of 15 minutes duration, each, were collected while the subject was falling asleep in the supine position. A 148-channel whole-head MEG (4-D Magnes WH2400) was used. Recording bandwidth was 0.1 to 100 Hz at a sample rate of 508 Hz.

Data were parsed into segments of 60 seconds duration. Each segment was analyzed and imaged, as follows. First, the covariance matrix was computed for the 0.1 to 100 Hz bandwidth. Beamformer coefficients were then computed for all voxels within the head boundary on a 3D grid with 5 mm spacing. Next, the data were filtered into the two specified frequency bands of interest for the sleep study – f_1: 8 – 11 Hz and f_2: 12 – 15 Hz – using 4th-order Butterworth IIR filters. This yielded two complete 60-second filtered data segments. The beamformer coefficients for location θ were computed from the unfiltered data were then applied to the filtered MEG data, giving the source waveform estimates for each frequency band:

$$\hat{S}_\theta(k) = \mathbf{W}_\theta^{\mathrm{T}} \mathbf{M}(k), \qquad (1)$$

where **W** is the beamformer coefficients, **M** is the MEG data, and k is the sample[1]. The source power for each frequency band is computed by integration of the corresponding source

---

[1] The notation for filtered MEG frequency band has been deleted, for simplicity.

waveform:

$$S_\theta^2(f_1) = \frac{1}{K}\sum_{k=1}^{K}\left[S_\theta(f_1,k) - \bar{S}_\theta(f_1)\right]^2,$$

$$\text{and} \quad . \qquad (2)$$

$$S_\theta^2(f_2) = \frac{1}{K}\sum_{k=1}^{K}\left[S_\theta(f_2,k) - \bar{S}_\theta(f_2)\right]^2$$

The beamformer noise power for each location θ was computed by weighted projection of the SQUID sensor noise:

$$N_\theta^2 = \sigma^2 \mathbf{W}_\theta^{\mathrm{T}} \mathbf{I}\, \mathbf{W}_\theta, \qquad (3)$$

where σ^2 is the mean SQUID noise variance in the bandwidth of f_1, and **I** is identity.

The frequency differential source power metric T is:

$$T_\theta = \left[S_\theta^2(f_1) - S_\theta^2(f_2)\right] \big/ N_\theta^2 \qquad (4)$$

This metric has a form analogous to Student's-T, and is unitless signal-to-noise ratio (SNR). This analysis is repeated for each voxel to create a functional image.

Functional images were computed for each 60-second segment of MEG sleep study data. These results were coregistered with the subject's MRI, and displayed using "mri3dX" software [6].

RESULTS

Frequency difference source power imaging revealed meaningful changes in oscillatory activity during wake and sleep stages 1 and 2. These patterns were sufficient to identify the subject's state, and agreed with polysomnogram classification.

The wake stage was characterized by alpha activity in the parietal and occipital lobes. Activity in the frontal lobes was balanced evenly between alpha and sigma frequencies, so they appear "silent" using this imaging method. An example of a waking source image is shown in Fig 1.

As the subject transitioned from wake to sleep stage 1, we observed a decline in posterior alpha activity and an increase in frontal sigma (relative to alpha). During sleep stage 2, activity in the parietal and occipital lobes are evenly balanced between alpha and sigma frequencies. Activity in the sigma frequency band significantly exceeds alpha in the frontal lobes. An example of a sleep stage 2 image is shown in Fig 2. The same pattern was observed in the other three subjects.

We also observed a consistent reduction in the peak value of T when transitioning from wake to sleep. This is not visible in the figures, as the functional images were normalized to their peak values.

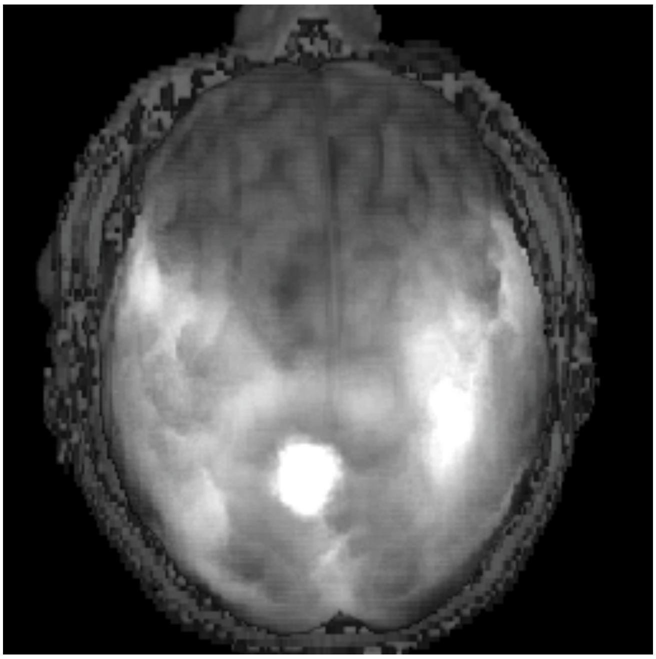

Fig 1. A beamformer image of a 60-second MEG data segment during wake stage is shown. During this stage, source activity in the alpha frequency band (8-11 Hz) is greater than sigma (12-15 Hz). This excess alpha power maps to the parietal and occipital lobes. By contrast, the difference in power between these two bands is very small in the frontal lobes.

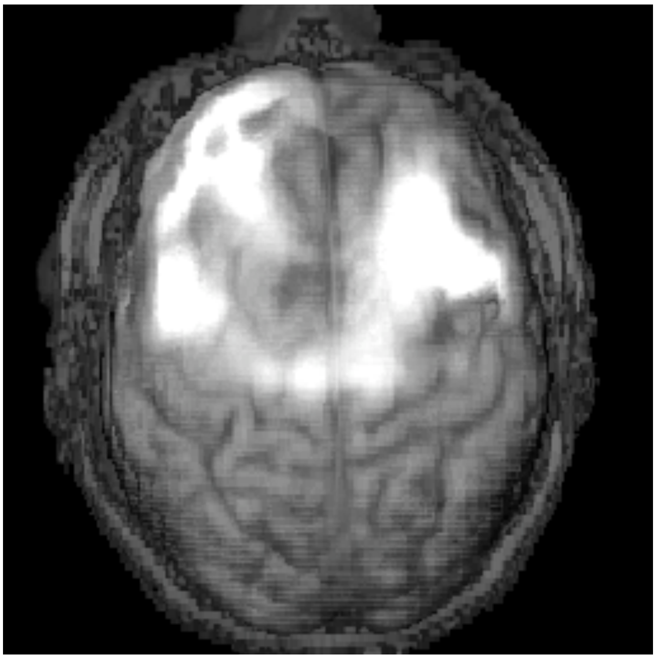

Fig 2. A beamformer image of a 60-second MEG data segment during sleep stage 2 is shown (same subject as in Fig 1). During this stage, frontal lobe source power in alpha band is less than that of sigma. In the parietal and occipital lobes, sigma and alpha power are nearly equal, so their difference is small. This image shows that activity in sigma band dominates in the frontal cortex.

DISCUSSION

We have successfully demonstrated a new functional imaging analysis for spontaneous unaveraged MEG measurements. Images of the differences in power between alpha and sigma frequency bands reveal source patterns that identify the wake or sleep stages, as determined by polysomnogram. Furthermore, the source activity distributions associated with each stage can be seen in all four subjects. These patterns, although part of the MEG data, are not evident using other analyses. Prior beamformer analyses generate functional images by comparing event-related differences in source power within a single fixed frequency band. Using that approach, the transition from wake to sleep is characterized only by a general decrease in source power throughout the cortex. As a result, no source pattern relating the subject's state to specific cortical structures can be discerned.

The images generated by this dual frequency analysis do reveal a relationship between rhythmic activity and state, but may be misinterpreted. For example, the appearance of frontal lobe activation in sigma band during sleep stage 2 (Fig 2) implies that sigma power exceeds alpha power. It should not be interpreted as meaning that sigma power increased. The measurements indicate that power actually decreased in both alpha and sigma bands.

An additional factor complicating the interpretation of functional images of frequency band power differences is that the LCMV beamformer shows uncorrelated portion of the signal, only. The alpha and sigma rhythms identified by visual inspection of unprocessed MEG and EEG recordings represent cortical sources that are correlated over a relatively large area. In a recent paper, fast alpha (sigma) spindles were localized to bilateral parietal cortex using dipole fit [7]. That result complements rather than contradicts the results of the two frequency beamformer analysis. It should be emphasized that each analysis method attempts to parameterize the measurements, within the constraints of the method. Using dipole fit to represent sigma spindle activity may not correctly localize extended source activity. Likewise, beamformer is blind to the extended source activity and only images compact dipolar sources that are not correlated with other source activity.

ACKNOWLEDGEMENT

This research was supported in part by NIH/NINDS Grant No. R01-NS30914. The authors wish to thank Dr. K.D. Singh for providing software for displaying the beamformer results on the cortical surface, and H. Robinson for rendering the figures.

REFERENCES

[1] Kato A, et al. (1999) Event-related desynchronization analyzed with SAM-SPM for functional brain mapping. In Yoshimoto T, et al, Eds., *Recent Advances in Biomagnetism*, 244-247.

[2] Robinson SE. (2004) Localization of event-related activity by SAM(erf). In Halgren E, Hamalainen M, Cohen D, Eds., *Proceedings of the 14th International Conference on Biomagnetism,* 463-464.

[3] Robinson SE and Rose DF (1993) Current source image estimation by spatially filtered MEG. In Hoke M, Erné SN, Okada YC, and Romani GL, Eds., *Biomagnetism: Clinical Aspects*, 761-765.

[4] Vrba J and Robinson SE (2002) SQUID sensor array configurations for magnetoencephalography applications. *Superconducting Sci. Technol.* 15: R51-R89.

[5] Vrba J and Robinson SE (2001) Signal processing in magnetoencephalography. *Methods* 25(2), 249-271.

[6] Singh KD (2008) mri3dx and mriWorkshopX are distributed as part of the BrainTools package.

[7] Urakami Y (2008) Relationship between sleep spindles and activities of the cerebral cortex as determined by simultaneous EEG and MEG recording. *J. Clin. Neurophysiol.* 25: 13-24.