Simultaneous MEG-intracranial EEG: New insights into the ability of MEG to capture oscillatory modulations in the neocortex and the hippocampus

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1. Introduction

Intracranial electroencephalography (iEEG) is indicated in epilepsy surgery candidates when noninvasive diagnostic techniques prove inconclusive (Bancaud et al., 1965). The objective of these recordings is to localize seizure foci as well as to prevent incidental resection of "eloquent" cortex that would result in significant cognitive deficits or paralysis (Wyler et al., 1988; Lesser et al., 1991). These recordings also provide rare but highly valuable data to test basic hypotheses in neurophysiology and cognitive neuroscience.

Using simultaneously acquired intracranial EEG data, it has become possible to validate noninvasive magnetoencephalography (MEG) results. While empirically evaluating the accuracy of various MEG/EEG source localization methods has been historically difficult, improved source localization with the millisecond time resolution that MEG provides can not only elucidate mechanisms of cortical function, but also provide further precision for planning of neurosurgical procedures, including functional mapping of tentative resection zones as well as placement of neural stimulators.

The relationship between neural activities recorded at various spatial scales remains poorly understood, partly because of an overall dearth of studies utilizing simultaneous measurements. We had the unique opportunity to record MEG simultaneously with intracranial EEG (iEEG) from electrodes implanted in the temporal and occipital lobes of four patients with epilepsy.

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2. Methods

A reading task was given to the patients, as described in Lachaux et al. (2008) and Dalal et al. (2009), adapted from Nobre et al. (1998). Each block lasted 6 minutes, and each patient participated in 4 blocks, for a total of 24 minutes of recording time per patient.

Task-related power modulations were detected in iEEG data by convolution with Morlet wavelets, as detailed in Dalal et al. (2009). A time-frequency beamformer was applied to MEG data to localize sources of task-related oscillatory modulations as per Dalal et al. (2008). In both cases, power modulations were calculated relative to a prestimulus baseline period.

Separately, to understand the contribution of various brain structures at different depths to the MEG signal, we also analyzed the cross-correlation of spontaneous hippocampus depth EEG traces with each MEG channel.

3. Results

Strong alpha/beta suppressions were observed in MEG reconstructions, in tandem with iEEG effects. While the MEG counterpart of high-gamma band enhancement was difficult to interpret at the sensor level in two patients, MEG time-frequency source reconstruction revealed additional activation patterns in accordance with iEEG results. In particular, gamma-band activity was observed up to 100 Hz with MEG source reconstructions, validated by gamma-band activity observed from intracranial EEG

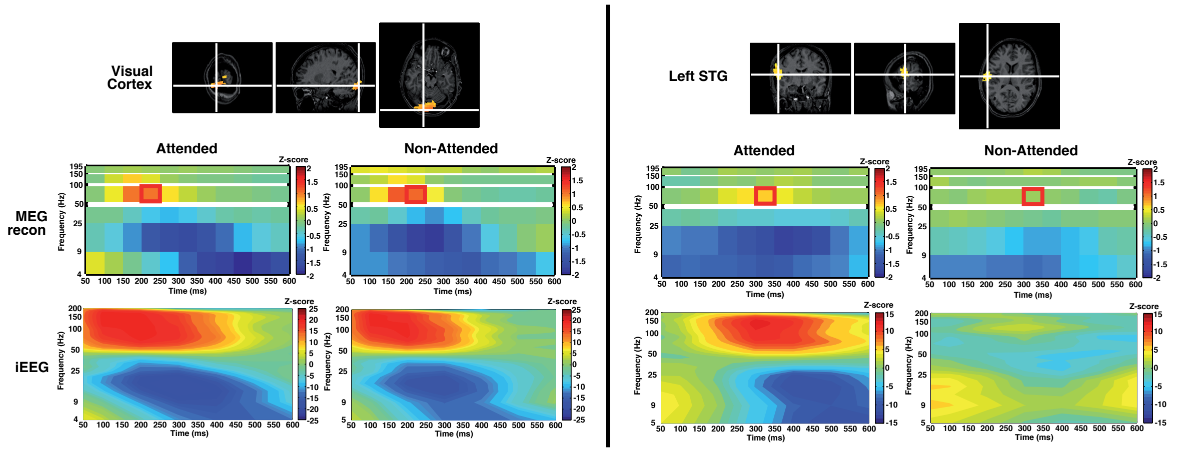

Figure 1: Spectral modulations derived from MEG source reconstruction compared favorably to those derived from intracranial EEG data. At left, the MEG reconstruction for a visual cortex source and the time-frequency map from the nearest intracranial EEG electrode, with power modulations up to 100 Hz detected with both techniques in both conditions. At right, the activity from left superior temporal gyrus (STG), showing task modulation of high gamma activity with both MEG source reconstruction and intracranial EEG. For each location, the activation maps superimposed on the structural MRI slices correspond to the MEG power modulation over the time-frequency window indicated by the red box on the MEG spectrogram.

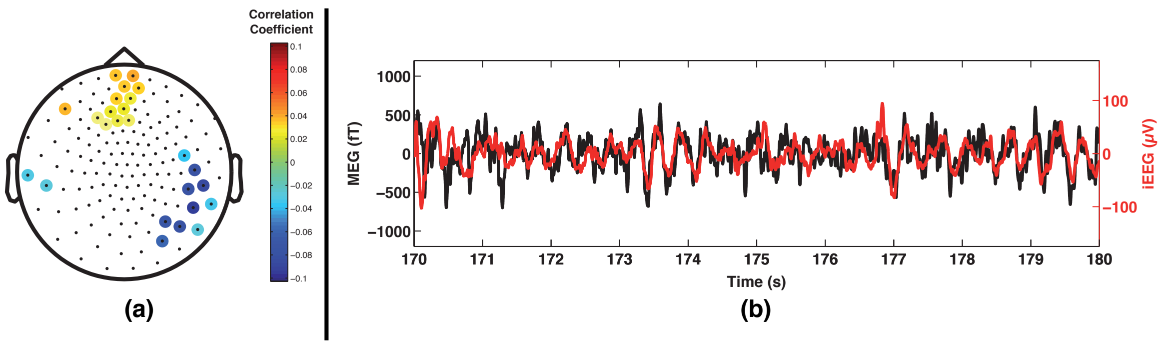

Figure 2: (a) Zero-lag correlation of a right hippocampus electrode with the MEG sensor array is shown as an MEG scalp topography. Sensors with peak correlations at non-zero lag are masked to eliminate spurious correlations due to neural connectivity rather than volume conduction. (b) In this trace, spontaneous theta oscillations are visible with zero-lag synchrony in the hippocampus depth electrode recording and the most correlated MEG sensor.

recordings in the vicinity of the MEG-derived peaks (Figure 1). The task additionally modulated both MEG-reconstructed gamma-band activity and intracranial EEG activity as expected, with occipital regions showing similar high-gamma-power increases with both task conditions, while superior temporal areas (associated with language) showed gamma-band-power increases only in response to attended words.

Depth EEG from the hippocampus demonstrated relatively strong correlation at zero-lag with patches of MEG sensors, often forming dipolar correlation patterns when visualized as scalp topography (Figure 2a). The lateralization of the topographies corresponded to the lateralization of the hippocampus implant. Often these correlations were strong enough such that theta oscillations from intracranial hippocampus electrodes could be directly observed in correspondence with similar MEG activity (Figure 2b). However, the sensor topographies were more complex than the overlapping spheres model often used for MEG forward modeling.

4. Results

These results suggest that source reconstruction techniques such as beamforming can increase the effective signal-to-noise ratio of MEG data, enhancing detection of gamma-band activity. They also indicate that the hippocampus generates magnetic fields strong enough to be detectable with modern whole-head MEG systems. However, robust MEG localization and reconstruction of such deep sources will likely require MEG forward models based on individual structural MRIs. As realistic head models based on MRI segmentations remain largely unvalidated, the method presented here may also be used to evaluate their performance and provide direction for improvement. More accurate head models will provide immediate benefits to source reconstruction techniques and potentially allow the reliable resolution of historically elusive brain structures.

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