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Technical Note

Real-time functional brain mapping using electrocorticography

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We demonstrate the feasibility of real-time cortical mapping from arrays of subdural electrodes using the electrocorticographic signal power in the higher spectral frequencies (76–200 Hz, or "χ-index"). Hand area was mapped offline in eight individuals using brief baseline and hand-movement measurements. In one patient, hand sensorimotor cortex was identified online during a handshake. We propose that this high-frequency component of the electrocorticogram provides a generic, reliable, clinically useful correlate of local cortical function.

Introduction

The gold-standard method of determining cortical functional organization in the context of neurosurgical intervention is electrocortical stimulation (ECS) which acts by disruption of normal cortical function to evoke movement or create transient functional disruption (Haglund et al., 1994; Keles et al., 2004). In contrast, methods that read endogenous signals, such as somatosensory-evoked potentials or fMRI, reflect normal cortical function. Electrocorticography (ECoG) has been suggested as another such method of mapping endogenous cortical function (Crone et al., 1998; Leuthardt et al., 2007; Miller et al., 2007a,b,c Pfurtscheller et al., 2003; Crone et al., 2006). Previous reports (Miller et al., 2007a,b, in press) suggested that broad spectral increases of the ECoG signal provide a correlate of local cortical activity, but that they are masked by changes in band-specific peaks at low frequencies (classically named event-related desynchronization, or ERD; Pfurtscheller and Lopes da Silva, 1999). In motor tasks, these conjugate processes cause behavioral splits at 48±9 Hz (±SD, hand) and 40±8 Hz (tongue) (Miller et al., 2007a,b,c). We aim to isolate this broad spectral increase, which we denote the "χ-index," by focusing well above these behavioral splits and well above 60 Hz line noise, choosing specifically from 76 to 200 Hz (our amplifiers have a built in low-pass at 200 Hz), to assess local cortical function (Fig. 1).

We illustrate that changes in power in the "χ-index" during repeated hand movement rapidly localize cortical hand area. These changes are characterized with only several seconds of data collection, giving a rapid, specific, and straightforward method for locating functional areas in cortex with the ECoG signal.

Methods

Electrocorticographic recordings in eight patients (mean age 35 years old (18–48 years old), 3 females) with peri-Rolandic (4 left-sided) subdural platinum electrodes (4 mm diameter, 1 cm inter-electrode spacing, Ad-Tech, Racine, WI) were recorded using SynAmps2 (Neuroscan, El Paso, TX) amplifiers, set to sample at 1 kHz and band-pass filter from 0.15 to 200 Hz. Data were collected and processed online at the bedside using the BCI2000 (Schalk et al., 2004) software on a laptop computer. Patients gave informed consent through a protocol approved by the University of Washington Institutional Review Board.

Each patient performed repeated opening and closing of the contralateral hand for 3-s blocks, alternating with equal periods of rest. Each block was visually cued, for both movement and rest periods. The hand movement was repeated 30 times, but only the first 5 blocks (15 s) of movement were used for this analysis. Ten seconds of baseline data were collected prior to movement blocks. All data were band-passed for the χ-index with a notch filter at 120 Hz to remove ambient noise. Log power in 80 ms windows of data (overlapping by 40 ms) was calculated throughout the task. The mean and standard deviation of the log power was determined for the baseline period, and, for the activity period, the baseline mean was subtracted from each windowed measurement, and scaled by the baseline standard deviation. A running sum of all data above 2 (in units of baseline standard deviation) was calculated for each channel. These sums are shown in bar plots,

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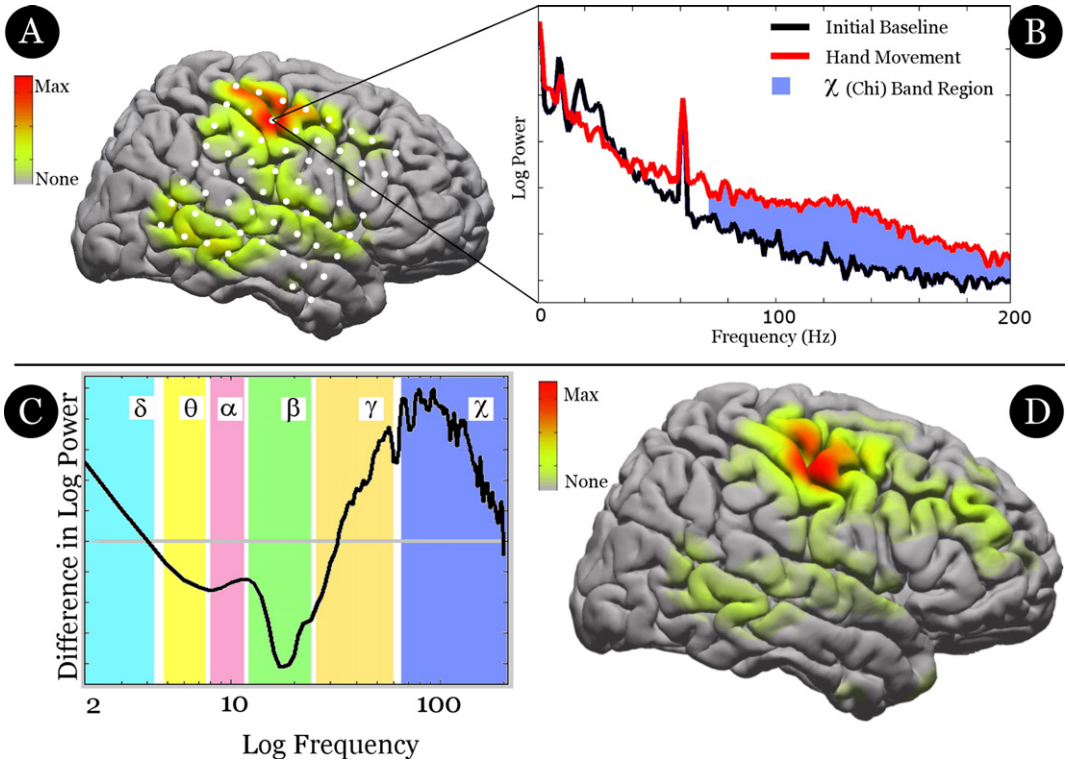

Fig. 1. Electrocorticographic motor mapping. (A) Map of hand movement compared to rest (patient G). Fifteen seconds of movement compared to a 10 s baseline (see methods) contributed to the interpolated map, scaled to the maximum response. Electrode locations are shown in white. (B) The spectrogram (mean log power vs. frequency) from a single, peri-central electrode, for hand movement (15 s) and resting baseline (10s). An increase in power occurs over a broad spectral range. This difference (shaded blue) is evident in even brief epochs of activity. (C) The difference in log power between movement and baseline, averaged across the most responsive electrode in each of 8 subjects, is shown along with spectral bands. The increase with movement is seen midway through the gamma band and extends to 200 Hz. The 'χ-index' is designed to capture the broad spectral power increase where separation between task and rest is most clearly observed. Note the classic decrease in α and β, and the broad increase in the χ-index (76–200 Hz). (D) Mean, superimposed, activation across all 8 patients, re-scaled to the maximum. A highly focal response is seen indicating the consistency of the change across subjects.

and interpolated on a standardized brain (Figs. 1 and 2). Weights were calculated for each channel by subtracting the mean across channels from each channel, thresholding at zero, and dividing by the maximum. Gaussian kernels centered at each electrode location were scaled by this amount and linearly superimposed to generate an interpolated cortical activation map, on the Talairach-standardized AFNI template cortex, for each patient. Electrode locations, in standardized Talairach coordinates, were calculated from post-implantation skull X-rays, using the LOC package (Miller et al., 2007a,b,c).

As significant changes were demonstrated within 2–3 s, we applied this prescription online for real-time brain mapping (a handshake – Fig. 3; Supplementary video) in one patient (patient C from Fig. 2).

Results

In each patient, localized activity was demonstrated for the first 15 s of movement (Fig. 2). In patient F, the initial activity map demonstrated weak motor but strong pre-motor activity. As she may have been developing familiarity with the task, a later 15-s block of movement was analyzed (beginning 30 s into the task) demonstrating stronger primary motor activation, with some remaining frontal activity. Based upon electrode locations in Talairach coordinates (Miller et al., 2007a,b,c), the strongest activation in each cortical map was consistently stereotactically localized to Brodmann Area 4, demonstrating efficacy in hand motor cortex identification (Fig. 2). In three patients, clinical stimulation mapping was performed and identified the same electrodes as this procedure (see Supplementary Fig. 2).

Real-time mapping (Fig. 3) demonstrated supra-threshold activity immediately upon initiation of the handshake, and showed clear delineation of hand sensorimotor cortex throughout the handshake.

Discussion

Change with activity in the electrocorticographic power in the χ-index (chosen here to be 76–200 Hz) was found consistently, for all 8 subjects, in a focal portion of cortex in classic hand areas. Unlike the power at lower frequencies, which, due to rhythms at specific frequency bands, may show little change or spatially broad decrease with motor function (e.g., mu rhythm) a reliable increase with function was found over the entire 76–200 Hz interval (Fig. 1). Previous studies looking up to 100 Hz have shown higher-frequency power (named "high gamma" by some) increases with motor function that are more focal (Crone et al., 1998; Leuthardt et al., 2007; Miller et al., 2007a,b,c; Pfurtscheller et al., 2003) than the power decreases at lower frequencies. High-frequency changes correlate with changes in the BOLD signal (Mukamel et al., 2005), and localized cortical dynamics have been specifically attributed to

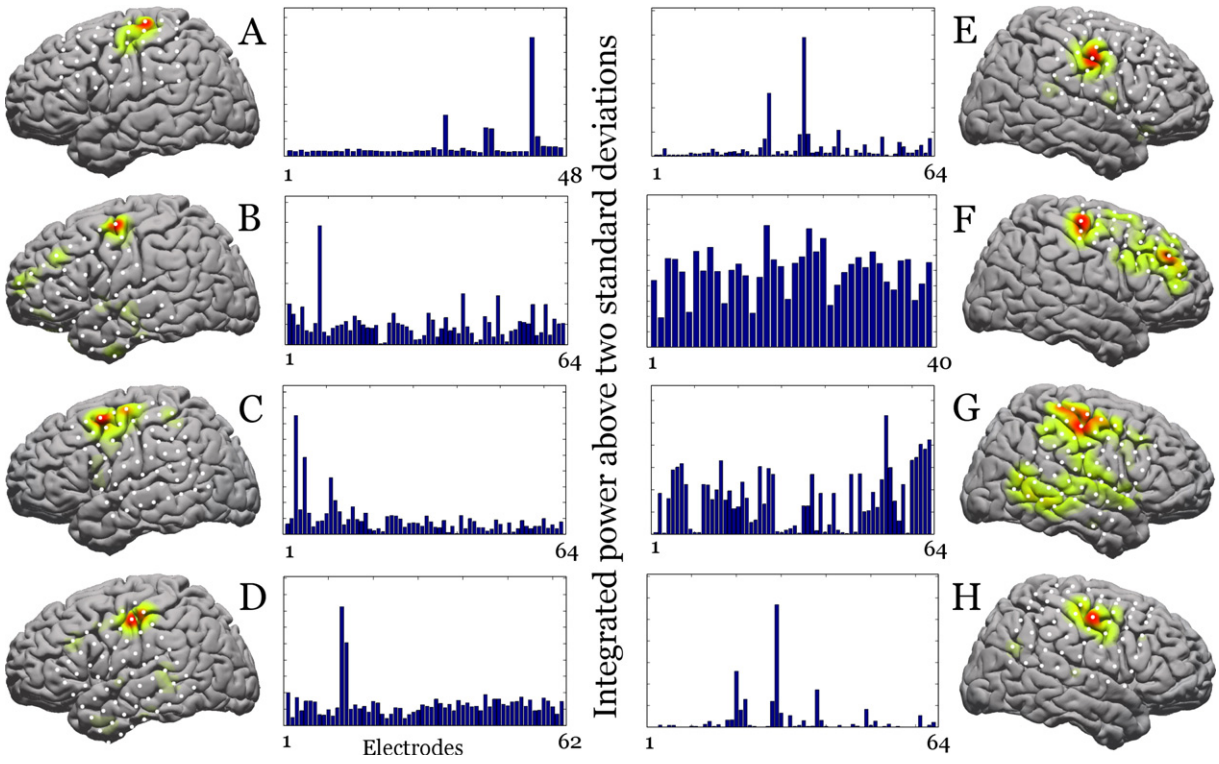

Fig. 2. Offline hand motor area mapping. Activation during hand movement as detailed in method section. The bar plots indicate the sum of suprathreshold activity for each electrode with corresponding interpolated brain plots for each patient. Electrode locations are in white. Note that the activation localizes to hand area in each individual, and that this activation in subjects A–E and H is very sparse. The first 15 s of motor activity was used except for pt F whose data is from 30–45 s into the task (see text).

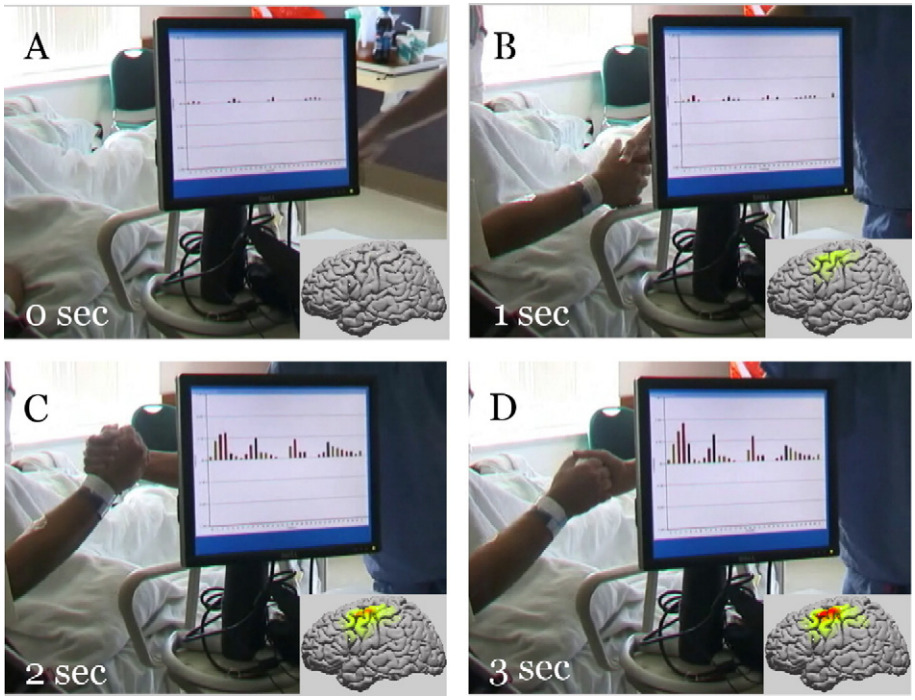

Fig. 3. Real-time identification of sensorimotor cortex. Four frames from a real-time video (with times at lower left) demonstrate evolution of the mapping during a three-stage handshake (in patient C from Fig. 2), following a 10-s baseline period. The inset brains demonstrate the cortical map throughout the, scaled to the final weight. The three stages of handshake of are shown in insets B–D. The full video is contained in the Supplementary material.

the 80–200 Hz band (Grenier et al., 2001). This real-time mapping technique should be robust across paradigms and brain areas, as focal high-frequency changes have been demonstrated in motor (Crone et al., 1998; Leuthardt et al., 2007; Miller et al., 2007a,b,c; Ohara et al., 2000), somatosensory (Bauer et al., 2006; Szurhaj et al., 2005), vision (Hoogenboom et al., 2006; Lachaux et al., 2005), auditory (Crone et al., 2001a,b; Edwards et al., 2005; Kaiser and Lutzenberger, 2005), memory (Sederberg et al., 2003), and language (Crone et al., 2001a,b; Sinai et al., 2005) paradigms. Previous reports of motor-related ECoG changes (Crone et al., 1998; Leuthardt et al., 2007; Miller et al., 2007a,b,c; Pfurtscheller et al., 2003; Crone et al., 2006) have required more elaborate post-acquisition analyses and long acquisition times (at least several minutes) to characterize cortical motor changes, and none have yet been implemented in real-time.

Using only the power in the "χ-index", rapid and reliable maps of cortical function can be obtained which agree with stimulation result. The results can be assessed immediately, in real time, and repeated if ambiguous. As the "χ-index" power appears to be a reliable marker of local cortical function, we propose that this method can be applied generically to clinical and research mapping of human cortex.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2007.05.029.

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