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MOVEMENT ASSOCIATED INCREASE IN THALAMIC BROADBAND SPECTRAL POWER IS A POTENTIAL FEATURE FOR BCI CONTROL

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ABSTRACT

Signals within the subcortical brain regions may be useful as control signals for brain computer interfaces (BCI). In this study we show, using a simple hand movement task, that focal increases in broadband spectral power, which are commonly used to control cortically-based BCI interfaces, may also be observed in the ventralis intermedius (VIM) thalamic nucleus, a key relay for the cerebellar outputs to the motor cortex that help to regulate voluntary movement.

INTRODUCTION

The cerebral cortex has been the predominant source for control signals in brain-computer interface (BCI) technologies to date, largely due to its direct involvement in motor control and sensory processing activities[1]. While this approach has yielded functional BCIs, tapping into the rich potential of subcortical structures such as the thalamus and other deep brain nuclei may confer distinct advantages. These regions, which play crucial roles in the modulation and relay of motor and sensory information, offer a different set of neural signals that could enhance the practicality, fidelity, and functionality of BCIs.

Among these deep nuclei, the motor thalamus is an intricate structure with functional topography parcellated by the motor homunculus and overlapping representations from basal ganglia and cerebellar nuclei. Such a configuration suggests its potential as a robust source of control signals for brain-computer interfaces. Within the thalamus, the motor homunculus representation of the entire body can be accessed within a spatial span of mere millimeters. Like cortical activity, thalamic movement related oscillatory activity in the beta frequency range (13-30 Hz) is suppressed during movement[2]. However, the broad spatial distribution of this desynchronization within the motor thalamus suggests it may be too diffuse to resolve somatotopic movement, constraining the scope of a BCI driven by this activity. Increases in broadband spectral power during movement are observed in motor cortex, with a distribution much more focal than for low frequency desynchronization[3]. Whether focal increases in

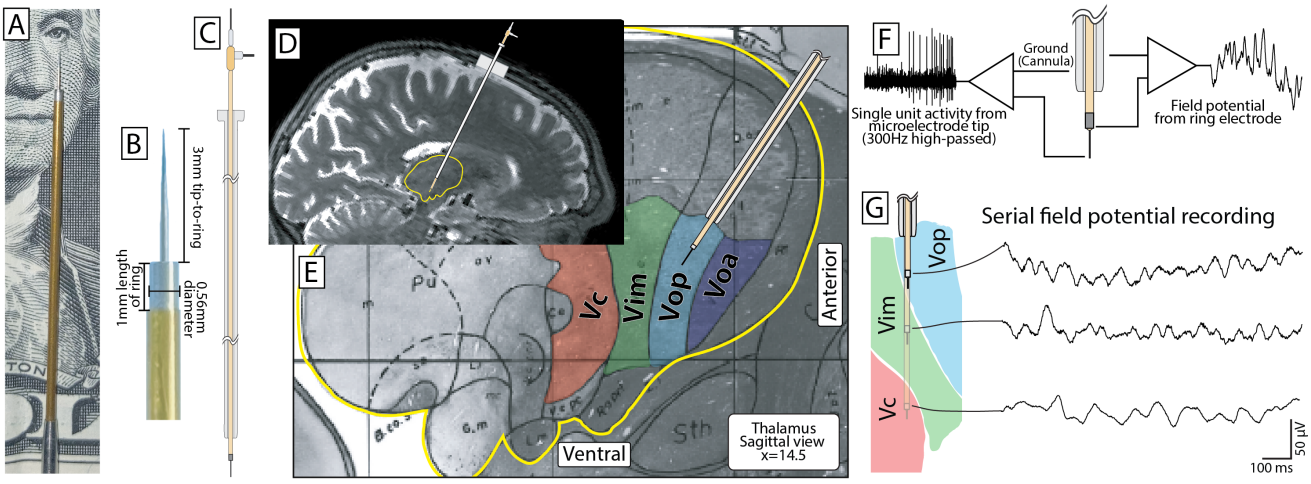

Figure 1: Experimental setup. (**A**) Recordings were obtained using a clinical DBS electrode both (B) with a high-impedance tip and with a low-impedance ring having surface area of 0.56 mm^2. The electrode was passed through a cannula (**C**) that had been inserted into the dorsal thalamus, as shown on a sagittal MRI slice (**D**), aligned along a trajectory targeting the VIM thalamic nucleus (**E**). (**F**) Local field potentials were recorded from the ring electrode and single unit activity was recorded from the microelectrode tip; the shaft of the cannula was referenced in all cases. (**G**) This study analyzes the field potentials at multiple evenly spaced sites along the trajectory recorded serially as the electrode was passed to target.

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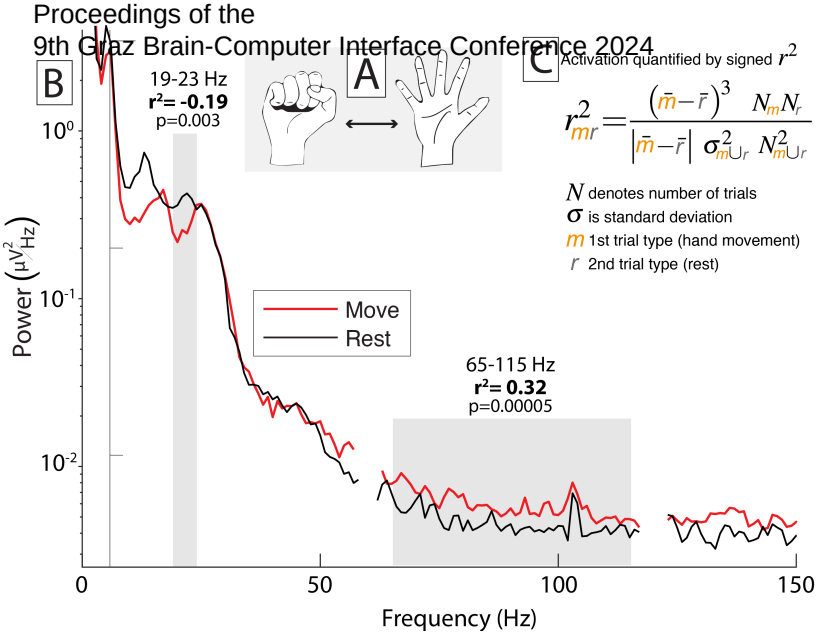

Figure 2: Movement associated spectral shifts. At each recording site, subjects performed a simple motor task alternating between (**A**) opening/closing of the hand and rest. (**B**) Averaged power spectral densities (PSD) from one recording site for Subject 1 are shown for movement and rest epochs. In this case, power within low frequency (<30 Hz) oscillations decreased during movement while broadband spectral power (65-115 Hz) increased. PSD for a subject were normalized to the global mean across all trials, and a signed r2 cross-correlation value was calculated from the mean PSD for movement versus rest trials, as shown in equation (**C**). The r^2 for both broadband change and change in a subject-specific 5 Hz wide low frequency band were computed.

broadband spectral power can be observed in this region has not been well studied.

The posterior region of motor thalamus, the ventral intermedius (VIM) nucleus, relays motor signals between cerebellum and motor cortex and is a key therapeutic target for deep brain stimulation treating tremor and other movement disorders[3]. This provides an opportunity to study the electrophysiology of motor thalamus during movement. In the present study, we recorded from the VIM nucleus in awake patients undergoing deep brain stimulation surgery for tremor and hypothesized that movement associated increases in broadband power would be observed.

MATERIALS AND METHODS

Subjects: Fourteen subjects undergoing deep brain stimulation electrode placement into the bilateral ventralis intermedius (Vim) nucleus of the thalamus for treatment of disabling tremor consented to participate in a research protocol during the awake surgery. The study and consent procedures were approved by Mayo Clinic's internal review board (IRB no. 19-009878).

Recordings: Serial thalamic recordings during task performance were obtained at multiple evenly-spaced recording sites (2 or 3 mm apart) as a microelectrode/macroelectrode (AlphaOmega Sonus STR-009080-00) was advanced towards the inferior border of the thalamus (Fig. 1). In 4 subjects, simultaneous recordings were obtained from two electrodes arranged parallel to each other along the anterior-posterior plane. Data were recorded to an AlphaOmega Neuromega system, referenced to the shaft of the electrode cannula and using a sampling rate of 44 kHz. Surface EMG was recorded using pairs of bipolar-referenced Ag/AgCl electrodes placed 2 cm apart overlying the forearm muscles for finger flexion/extension.

Motor Task: At each recording site, subjects were verbally and visually cued for two alternating conditions: 1) rest, 2) continuous opening/closing movements of the dominant hand. Individual task epochs were 5 seconds in duration. The sequence was repeated 20 times per site. Compliance with the task was assessed in real-time by monitoring of EMG activity.

Power Spectral Density and Cross Correlations: All analyses were performed in Matlab. Epochs of rest versus movement were manually segmented via visual inspection of the rectified EMG; ambiguous epochs were rejected.

Averaged power spectral densities (PSD) for individual movement or rest epochs were calculated from 1 to 300 Hz, with 1 Hz frequency resolution, using Welch's method of overlapping periodograms with a 1 second Hann window and 0.5 second overlap to attenuate edge effects. Averaged PSDs were then normalized to the global mean across all trials.

At each recording site, we calculated signed r^2 cross-correlation values (r^2) by comparing the mean PSD between movement and rest trials (Fig. 2). As a proxy for broadband activity, r^2 was calculated for the 65-115 Hz band (avoiding line noise at 60 and 120 Hz). Because the center frequency for movement-related oscillations in the lower (<30 Hz) frequency bands varied between subjects, we systematically determined for each subject which 5 consecutive frequency bins, within the range of 8-30 Hz, was able to maximally discriminate between movement and rest as follows: 1) r^2 values for each 1 Hz bin within the 8-30 Hz range were averaged across all recording sites in a subject and 2) the 5 contiguous bins with the highest sum of r^2 values was selected.

Plotting Power Changes on Subject-Specific MRI: The site of each recording relative to the final lead position was known, allowing for MRI coordinates for each recording site to be computed using offsets to the lead artifact as seen on a postoperative CT scan co-registered to a preoperative T1-weighted MRI using mutual information in SPM12. The MRI was resliced in plane with recording sites and served as the background on which data was plotted[5].

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Separate plots were prepared for movement associated power changes in the low frequency band and in broadband. We set significance at 0.95, uncorrected. Recording sites with a significant r^2 were plotted in red (movement associated increase) or blue (movement associated decrease), with the sizes scaled to the maximum r^2 value for that subject. Sites without significant power change were plotted with a white circle of fixed diameter.

RESULTS

Broadband Spectral Changes: Example power spectral densities (PSD) for movement and rest epochs from one recording site for Subject 1 are shown in figure 2B. Figure 3 shows the spectra at each recording site for this single subject (A) and r^2 maps for the low frequency band (B) and broadband (C). A significant increase in broadband power during movement was observed in at least one recording site for 8 of the 14 subjects (r^2_{max} range = 0.11-0.44) (Fig 4C). Sites showing significant broadband power increase were most often found at the inferior recording sites, in the dorsal thalamus near the predicted region of the VIM nucleus.

Low Frequency Oscillations: We found that the low frequency band showing the greatest power change with movement varied between subjects, from as low as 8-12 Hz, up to 20-24 Hz. Significant decreases in power within the subject-specific low frequency bands were present in at least one recording site for 11 of 14 total subject (data not shown), and for 5 of the 8 subjects with increase in broadband (Fig. 4c). In two cases (subjects 6 and 7) there was increased power within the band, and in one (case 8) there was no significant change with movement. Sites showing significant a power decrease in the low frequency band were widely distributed through the sampled region of dorsal and ventral thalamus.

DISCUSSION

We show that a focal movement associated increase in broadband spectral power may be observed in the VIM thalamus during voluntary movement. In our subjects, increases in broadband power tended to be more spatially

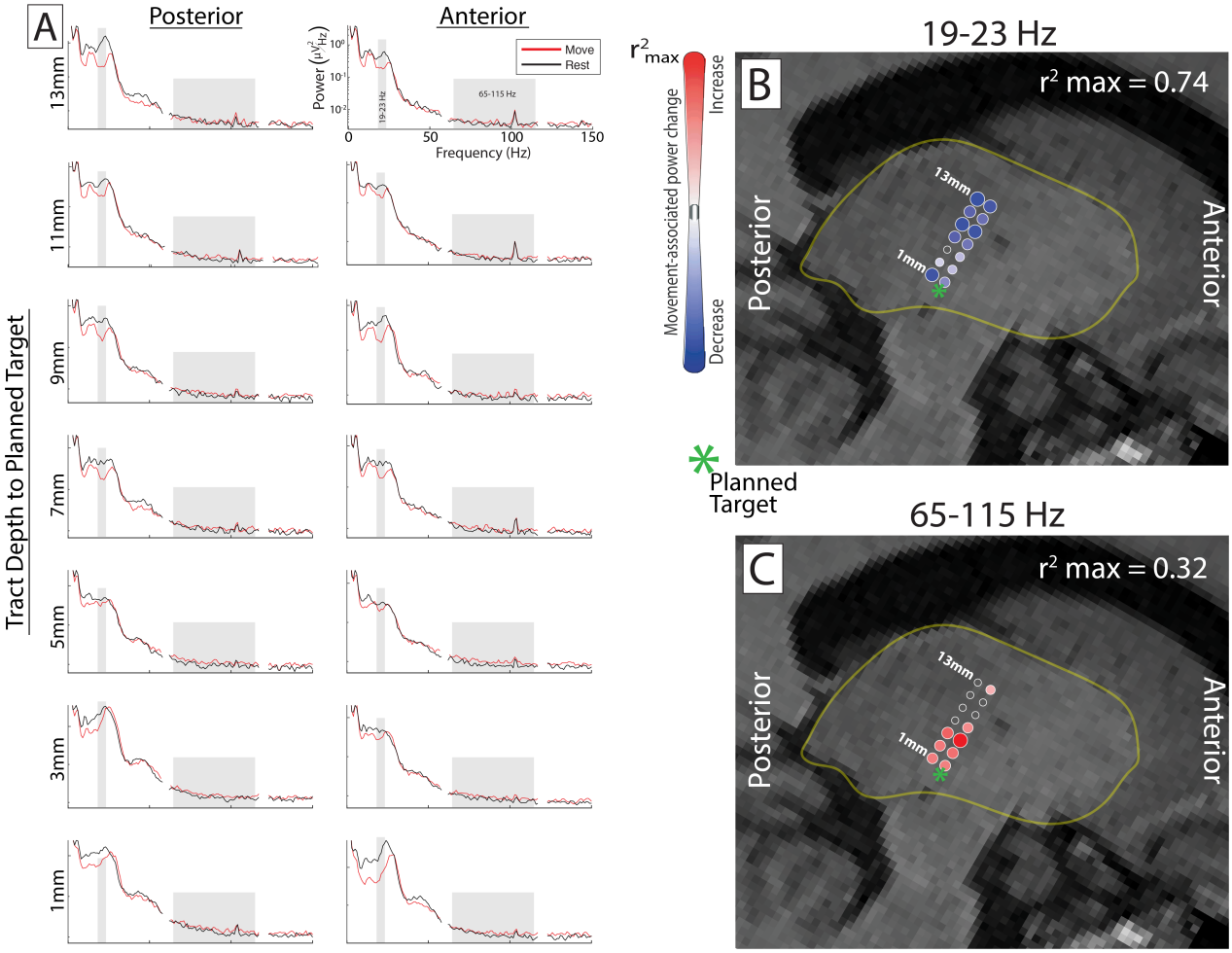

Figure 3: Spectra and r^2 plots for a single subject. (**A**) Average power spectral densities during movement (red) and rest (black) shown for each of 14 recording sites sampled in subject 1. The low (19-23 Hz) and broadband (65-115) frequency ranges are highlighted with gray boxes. The r^2 values at each site are shown for (**B**) the 19-23 Hz band and (**C**) the 65-115 Hz band as dots plotted on sagittal T1 MRI slice. A red dot indicates an increase in power with movement, and a blue dot indicates a decrease. The size of each dot represents the absolute value of r^2 scaled to the maximum r^2 value for the frequency band (as shown in upper right-hand corner of each plot). In this subject, the sites were arranged along two parallel tracts 2mm apart in the anterior/posterior plane with serial recordings taken every 2 mm during electrode decent to the planned target (green asterisk).

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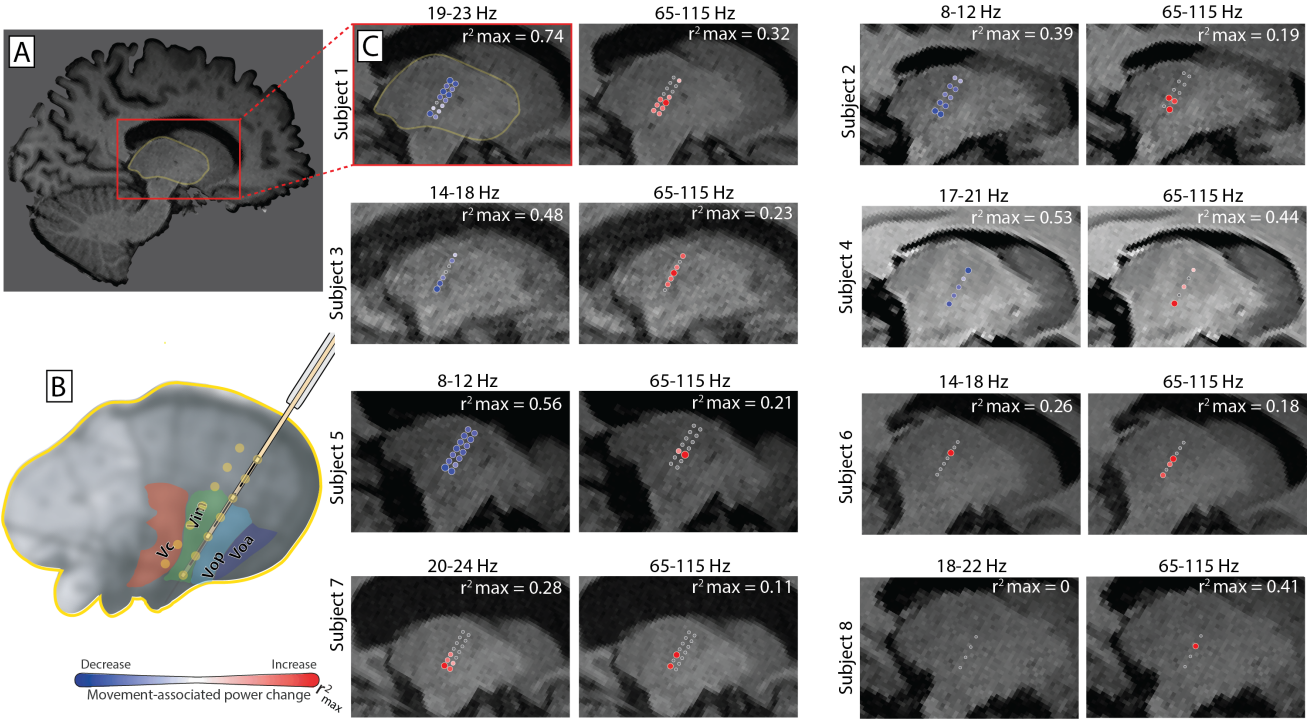

Figure 4: Subjects with significant increase in broadband spectral power during movement. (**A**) A sagittal T1 MRI slice from subject 1, showing the thalamus (yellow outline) and the cropped/enlarged region used for r^2 plots (red box). (**B**) Cartoon thalamus showing the ventral sensorimotor nuclei including the VIM target. Approximate recording locations are shown relative to these nuclei for the case of two parallel tracts (anterior/posterior) and for seven recording sites spaced 2mm apart. (**C**) All subjects with significant movement associated broadband increase. The r^2 at each recording site is plotted on a sagittal T1 MRI for both the subject specific low frequency band and broadband. Red dots indicate and increase in spectral power with movement, blue a decrease. The size of each dot represents the absolute value of r^2, scaled to the maximum r^2 value for that band.

discrete than were the desynchronizations of low frequency oscillations, as has been seen previously in motor cortex.

However, we did not observe broadband power increases in nearly half of the subjects. This may be because the frequency range of interest approaches the noise floor of our recording paradigm. Also, the operating room has many idiosyncratic sources of electrical noise which vary from case-to-case and even through the course of a single surgical case.

In most patients, a diffuse desynchronization of low frequency oscillations was seen during movement. Qualitative review of the spectra shows that there is often more than one oscillation in this range, and that in some cases the center frequency of the most prominent oscillation shifted with movement. Therefore, our limiting analysis to the 5 Hz band yielding the highest r^2 value was an overly simplistic approach.

It is possible that the serial nature of recordings allowed subtle changes in behavioral state of the patient (attention, etc.) to confound results. This may be one explanation for the patchy spatial distribution of responses in a few subjects. Future studies will focus on simultaneous recordings at multiple sites during simple hand movements to allow for a more consistent behavioral state under which power differences across the recording sites can be more directly compared.

Upcoming work will include simple hand/tongue/foot movement tasks and radially segmented recording electrodes to attempt to resolve somatopic representation using the broadband power shifts we report in this study.

CONCLUSION

We find that focal increases in thalamic broadband spectral power are detected in a majority of subjects during a simple hand movement task. Further studies are needed to determine if this may be a signal robust enough to serve as an alternative control for BCI applications.

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