Proceedings of the
9th Graz Brain-Computer Interface Conference 2024

10.3217/978-3-99161-014-4-023

IDENTIFYING NEW FEATURES FOR BCI CONTROL: SPECTRAL CHANGES IN THE MOTOR THALAMUS REVEAL HAND REPRESENTATION DURING OVERT AND IMAGINED MOVEMENT

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ABSTRACT: This study explores the potential of the ventral intermediate nucleus (VIM) of the thalamus as a subcortical signal source for brain-computer interfaces (BCIs). We analyzed spectral changes in the VIM for overt and imagined hand movements during deep brain stimulation (DBS) lead implantation surgery. During task periods, we found suppression of power in the stereotypical beta range (13-30 Hz). Only in one recording site did we find a significant increase in broadband power (65-115 Hz) with overt hand movement, but not for imagined movement. We provide evidence that motor representation in the VIM could act as a subcortical control signal for future BCI applications.

INTRODUCTION

In recent years, brain-computer interfaces (BCIs) have seen remarkable advances, particularly in motor control and rehabilitation tasks. A critical component of BCIs is the ability to sense and accurately decode neural signals into actionable commands, restoring the dysfunction between intent and action seen in many disorders of the motor system. Current BCI applications typically involve electroencephalography (EEG), magnetoencephalography (MEG), electrocorticography (ECoG), or intracortical microelectrode array recordings of the motor or sensory cortices [1–4]. However, identification and development of BCI's using subcortical neural signals may provide several advantages for future applications: (1) subcortical targets may provide unique information regarding motor planning and coordination (2) can be integrated into existing neuromodulation technologies like deep brain stimulation (DBS), and (3) may be necessary in patients with focal damage to cortical regions [5].

The ventral intermediate nucleus (VIM) of the thalamus plays a pivotal role in the modulation and relay of motor signals between the cerebellum and the motor cortex and is a major target of DBS therapy for movement disorders [6]. However, its potential as a BCI signal is unclear.

In this case study, we measured spectral changes in the VIM during overt and imagined hand movements during DBS intraoperative microelectrode macro recordings. During task periods we found significant suppression of power in the stereotypical beta range (13-30 Hz) compared to rest periods. In one recording site, we found a significant increase in broadband power (65-115 Hz) with overt hand movement, but did not observe this as a general phenomenon or in imagined movement conditions. Overall, our findings suggest that the VIM could act as a control signal for future BCI applications.

MATERIALS AND METHODS

Patient and surgical implantation: A 49-year-old male patient with multiple sclerosis (MS) presented for bilateral DBS electrode implantation of the ventral intermediate nucleus of the thalamus (VIM). The patient was diagnosed with MS at age 21 after optic neuritis, followed by multiple relapses. He previously received disease modifying therapy including interferon beta-1b and mitoxantrone. MRI revealed multiple lesions throughout his cervical spine, and supratentorial periventricular and juxtacortical white matter, no lesions were seen in the posterior fossa. At age 27 he developed gradual onset of right greater than left sided tremor, with kinetic greater than postural component. At the time of his present evaluation, his only disability was related to his tremor. The patient consented to participate in a research protocol during the awake surgery for implantation of these leads. Mayo Clinic's internal review board approved the study and the consent process (IRB no. 19-009878). Stereotactic targeting and alignment to the left VIM was performed with the Leksell G frame (Elekta, Stockholm, Sweden) and Stealth system (Medtronic, Minneapolis, MN). A cannula was stereotactically passed to the VIM (Fig. 1-2). From the tip of the cannula, a microelectrode (0.5–1 MΩ platinum–iridium; FHC, Bowdoin, ME) was advanced 15 mm to a target in the VIM (Fig. 1).

Motor Task: Data were collected during a motor task involving opening and closing of the hand. The patient

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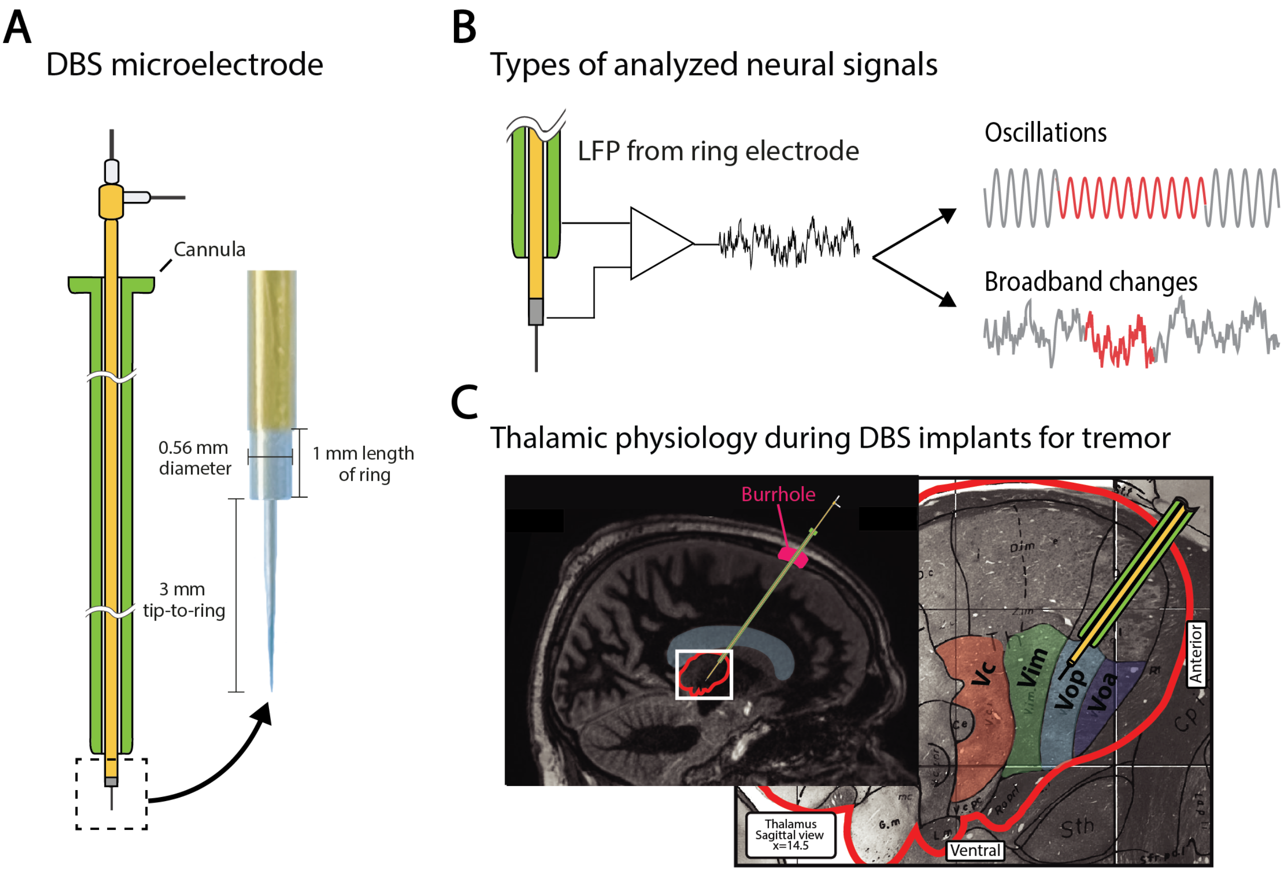

Figure 1: **Deep brain stimulation (DBS) microelectrode recordings (A)** Microelectrode recording schematic, micro tip, and macro ring dimensions. **(B)** Micro and macro neural signals are referenced to the cannula and can inform about specific signal modalities. Local field potentials (LFP) analyzed from the macro ring can uncover neural oscillations and broadband changes. **(C)** Microelectrode recordings are used during thalamic DBS implants to map thalamic neurophysiology. Serial microelectrode recordings may help inform about thalamic anatomical subregions and DBS lead placement. Thalamic anatomy background included from [7].

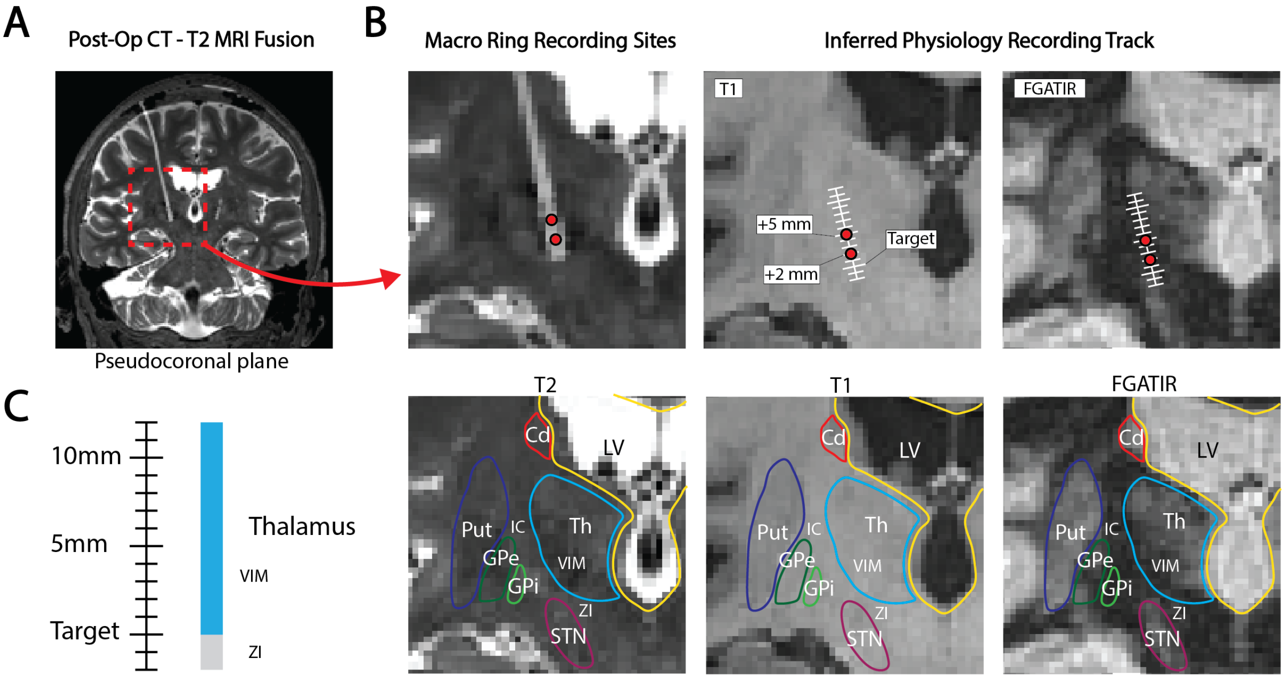

Figure 2: **DBS lead localization and anatomical segmentation (A)** Post-op CT - T2 MRI fusion showing final lead position on brain anatomy. Pseudocoronal image is resliced in-plane with DBS lead while maintaining midline symmetry. **(B)** Identification of thalamic microelectrode macro ring recording sites through lead localization. **(C)** Inferred anatomical segmentation along physiologic recording track.

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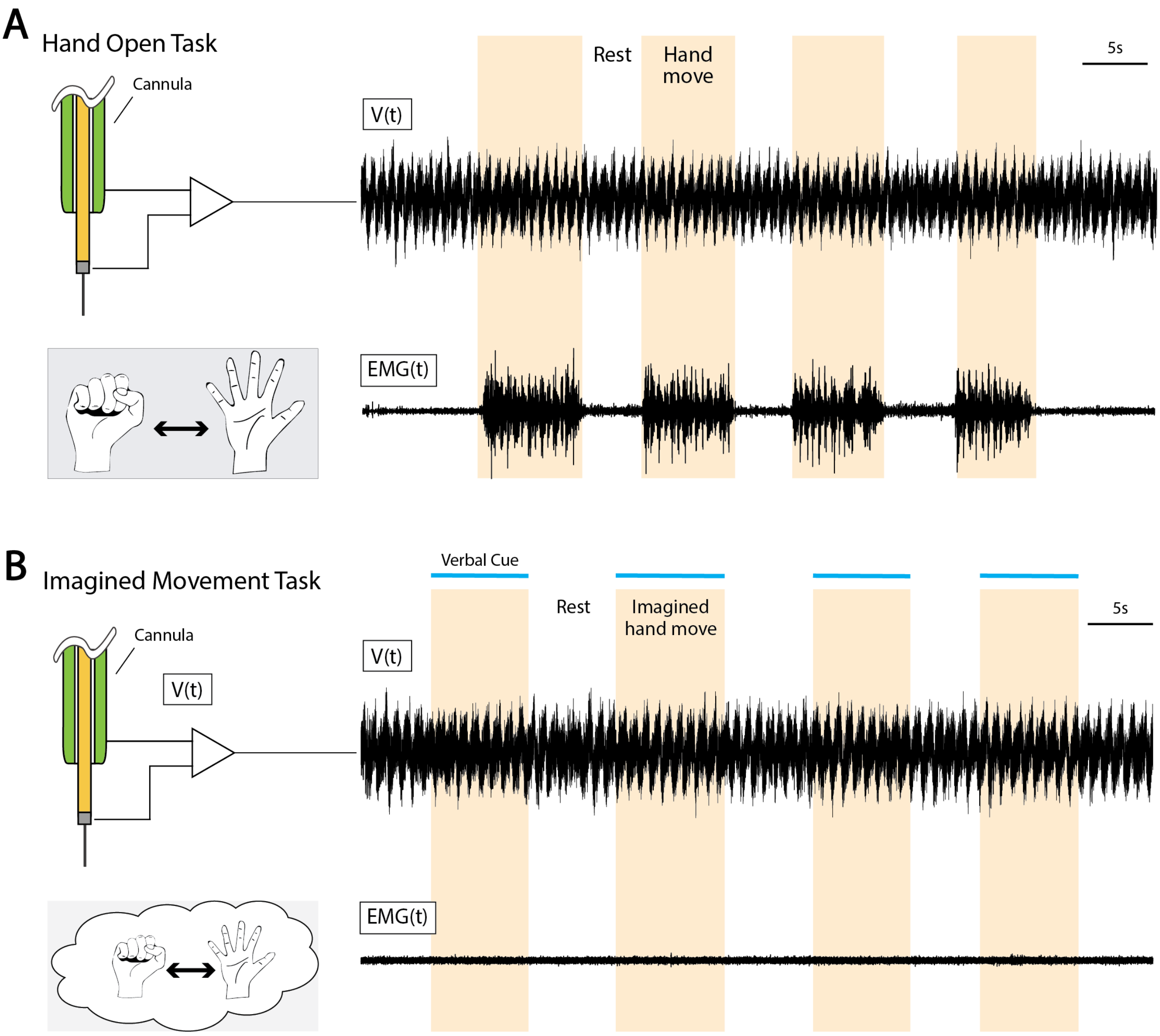

Figure 3: **Physiologic recordings and behavioral tasks (A)** Microelectrode ring recordings are referenced to the cannula and are recorded over rest and movement periods for a hand open task. Movement periods are segmented by EMG signal. **(B)** For the imagined movement task, the patient was verbally cued to imagine hand opening.

was verbally cued to perform a simple self-paced movement (or imagined movement) with interleaved rest periods. After twenty trials of movement were performed, the task was repeated for kinesthetically imagined movement (Fig. 3). These tasks were chosen based on prior work, which has produced clear results in recordings from brain surface and depth electrodes [8, 9].

Electrophysiological recordings: Microelectrode recordings were referenced to the cannula. Voltage time series were recorded with an Alpha Omega system (Alpha Omega, Israel). Recordings were sampled at 44 KHz. EMG was measured from the forearm extensors/flexors and synchronized with microelectrode ring recordings.

Lead localization: As illustrated in Fig. 2, microelectrode recording position was determined by co-registration of the postsurgical CT, which includes electrode artifact, and the pre surgical MRI using a normalized mutual information approach. This fused image was then resliced in plane with the DBS lead position using custom MATLAB code [10]. T1, T2, and FGATIR MRI series were overlaid to reveal thalamic and surrounding anatomical borders.

Signal processing and analysis: Within each movement or movement imagery trial, averaged power spectral densities (PSDs) were calculated from 1 Hz to 300 Hz every 1 Hz using Welch's averaged periodogram method with 1 second Hann windows and 0.5 second overlap to attenuate edge effects. These trials were defined based on 1) EMG during the movement task, and 2) timing of verbal cuing during the kinesthetic imagery task. Average power from 65-115Hz was used to localize broadband activity as done previously in cortical studies [9]. This range was chosen as it is well above the known range of

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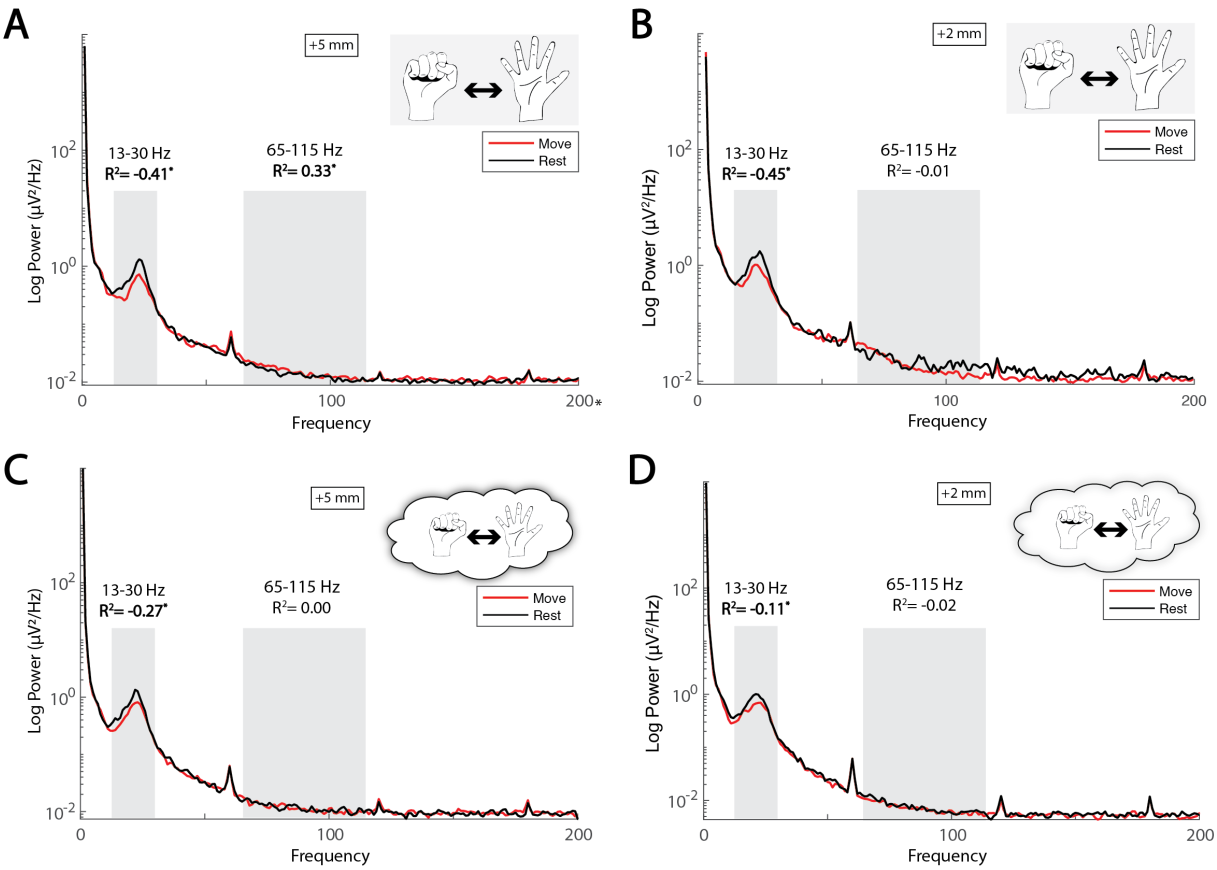

Figure 4: **Power spectral densities for behavior tasks (A)** The open hand task at +5mm from target showed significant suppression in the stereotypical beta range (13-30 Hz) and a significant increase in the broadband frequency (65-115 Hz) with hand movement. **(B)** At +2mm from target, hand movement was associated with a beta range suppression, but no significant change in broadband. **(C)** Imagined hand movement at +5mm and +2mm **(D)** from target were associated with significant beta range suppression, but no changes in broadband frequencies. * and bold text indicates $p < 0.05$ for paired-samples t-test of rest and move conditions.

most oscillations and avoids ambient line noise at 60 Hz and 120 Hz.

For each task and recording site, we calculated separate signed r^2 cross-correlation values (r^2) of the mean spectra from 13-30 Hz and 65-115 Hz. the sign indicates whether power is increasing or decreasing with each task. To calculate a p value for each site and task, we performed a paired-sample t-test comparing 13-30 Hz and 65-115 Hz power for task trials and the rest trials that immediately follow.

RESULTS

Field potentials were measured at two VIM locations, +2 and +5mm from the DBS lead implant depth (Fig. 2) during the overt and imagined hand movement tasks. In all recording sites a clear oscillation peak emerged in the stereotypical beta range between 13-30 Hz (Fig. 4). During overt hand movement, there was a significant decrease in beta power at both +2 mm (r^2= -0.45, p = 1.2x10^{-}6) and + 5 mm (r^2= -0.41, p = 1.4x10^{-}6) recording sites. At the +5mm recording site there was a significant increase in broadband power (65-115 Hz; r^2= 0.33, p = 2.3x10^{-}5), but no significant increase at the +2mm site (r^2= -0.01, p = 0.62). For the imagined hand movement task, we also found significant decreases in beta power at both +2 mm (r^2= -0.11, p = 0.04) and + 5 mm (r^2= -0.27, p = 4.26x10^{-}4) recording sites. We did not observe any significant increases in broadband power at either +2mm (r^2= -0.02, p = 0.42), nor +5mm (r^2= 0.00, p = 0.86) depths during imagined movements.

DISCUSSION

Beta power suppression, characterized by a decrease in the beta frequency band (13-30 Hz) is a well-documented feature in cortical and subcortical motor circuits related to motor planning, execution, and suppression [11]. This beta band has been utilized for a variety of BCI applications, however primarily from motor cortical regions [12]. Our findings suggest that the beta suppression observed with movement in the VIM may also be a suitable control source for future applications.

In primary motor cortex, studies have also found a broadband spectral increase above 50 Hz that we measure between 65 Hz and 115 Hz, which is generally correlated

10.3217/978-3-99161-014-4-023

to neural population firing. These broadband increases are typically more focal than the beta suppression phenomenon, and have similarly been utilized as BCI control signals. While we observed an increase in broadband at the +5mm recording site for overt movement, this was not a general phenomenon in both depths or across tasks - contrary to other motor cortex BCI studies [13]. Similar to other motor structures, the motor thalamus has somatotopic organization. Specifically, the VIM is organized continuously rostrocaudally [14]. It is unclear whether an increase in broadband does not occur in the VIM with imagined movements, or whether our lack of findings could be due to spatial sampling or amplifier noise floor limitations in the intraoperative DBS setting. Future studies will examine the directional somatotopic organization for different types of overt and imagined movements to further investigate this feature.

CONCLUSION

Overall, we found beta band suppression in the VIM with overt and imagined movements which could act as a subcortical control signal for future BCI applications.

ACKNOWLEDGEMENTS

We are grateful to the patient who volunteered their time to participate in this research. This work was supported by the NIH U01-NS128612 (KJM), Brain and Behavior Research Foundation (KJM), and the Foundation for OCD Research (KJM). The contents of this manuscript are solely the responsibility of the authors and do not necessarily represent the official views of the NIH. Our funders played no role in data collection and analysis, study design, decision to publish, or manuscript preparation.

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