# Electrocorticographic Activity of the Brain During Micturition

Tracie Tran, Po T. Wang, Brian Lee, Charles Y. Liu, Evgeniy I. Kreydin, Zoran Nenadic, An H. Do

*Abstract*— **Current therapies for neurogenic bladder do not allow spinal cord injury patients to regain conscious control of urine storage or voiding. Novel neural technologies may provide means to improve or restore the connection between the brain and the bladder; however, the specific brain areas and their underlying neural activities responsible for micturition must be better understood in order to design such technologies. In this retrospective study, we analyzed electrocorticographic (ECoG) data obtained from epilepsy patients who underwent ECoG grid implantation for epilepsy surgery evaluation, in the hopes of determining specific electrophysiological activity associated with micturition. Our results indicate modulation of the delta (δ, 0.1-4 Hz) and low-gamma (γ, 25-50 Hz) activity in the peri-Sylvian area and the inferior temporal lobe. These findings suggest involvement of the insular cortex and the uncinate fasciculus in micturition, important structures related to sensation and decision making. To date, this is the first known study utilizing ECoG data to elucidate the electrophysiological activity of the brain associated with bladder control and sensation.**

***Index Terms***— Neural technologies, neuromodulation, neurophysiology, neurogenic bladder, electrocorticogram

## I. Introduction

Neurogenic bladder dysfunction is a common complication of conditions such as spinal cord injury (SCI), multiple sclerosis, and stroke due to the interruption of pathways from the brain to the lower urinary tract. It is estimated that 80% of multiple sclerosis patients, 70-84% of spinal cord injury patients [1], and 19% of stroke patients 6 months post-admission have some degree of bladder dysfunction [2]. For example, in people with SCI, lesions almost universally interrupt descending and ascending pathways between the brain and the urinary system (i.e. pontine and sacral micturition centers), leading to some degree of impairment in bladder motor control and sensation [3]. Neurogenic bladder can lead to lower quality of life, depression and psychological distress [4]. Furthermore, it is considered one of the highest rehabilitation priorities amongst individuals with neural injuries [5]. Frequent complications of neurogenic bladder include increased risk of urinary tract infections and stones, nephropathy, and isolation due to embarrassment in social situations. Current treatment options of neurogenic bladder include medications, catherization, or electrical stimulation to facilitate voiding and minimize incontinence [6]. However, none of these therapies are satisfactory and ultimately, do not fundamentally improve or restore the connection between the brain and the lower urinary system.

Emerging neuro-technologies such as those based on neuromodulation or neuroprosthetics can potentially help improve or restore the connection between the brain and the urinary system. The successful design of neuromodulation protocols or neuroprostheses for neurogenic bladder will require detailed knowledge of how the brain controls the process of micturition. However, the brain areas and electrophysiological features underlying bladder voiding and fullness sensation remain poorly understood. Previous neuroimaging studies implicated that several brain areas are involved in bladder control and sensation [7]. More specifically, functional magnetic resonance imaging (fMRI) studies have shown that the periaqueductal gray is active during bladder filling [7], consistent with its role as a relay center for sensory afferents from the bladder to the insula, which processes visceral sensations. FMRI studies have also demonstrated that the prefrontal cortex is active during micturition [8]. Since the prefrontal cortex's function includes planning and controlling social behavior, it is believed that this area is important for making the conscious decision to urinate at a socially appropriate time and setting. Furthermore, the prefrontal cortex's control of conscious voiding is likely facilitated by the sensory information it receives via connections to the periaqueductal gray [8]. Similarly, positron emission tomography (PET) studies showed increased metabolism during micturition in the inferior insular cortex, periaqueductal gray, and the pontine micturition center [9], suggesting that there is an increase in neural activity in these areas. Although these studies provide some insight into what brain areas are involved in bladder voiding and sensation, the low temporal resolution of fMRI and PET precludes understanding of the neurodynamic processes involved in micturition. In addition, these neuroimaging modalities provide only indirect measure of underlying neural activity. Therefore, deeper understanding of the brain's involvement in bladder control and sensation requires that the underlying neurophysiological process be directly measured at a sufficiently high temporal resolution.

Motivated by this knowledge gap, this study sought to explore what cortical areas and electrophysiological features are consistently associated with bladder control. To this end, electrocorticography (ECoG) recordings from subjects monitored for epilepsy evaluation were retrospectively analyzed to determine band patterns associated with micturition. Based on prior neuroimaging studies and general

T. Tran and A.H. Do are with the Department of Neurology, University of California Irvine, Irvine, CA 92617 USA. (e-mail: traciet@ uci.edu; and@uci.edu).

P. T. Wang and Z. Nenadic are with the Department of Biomedical Engineering, University of California Irvine, Irvine, CA 92617 USA. (e-mail: ptwang@uci.edu; znenadic@uci.edu).

B. Lee and C. Y. Liu are with the Department of Neurosurgery, University of Southern California, Los Angeles, CA 90033 USA. (e-mail: brianlee@usc.edu; cliu@usc.edu).

E. Kreydin is with the Department of Urology, University of Southern California, Los Angeles, CA 90033 USA. (e-mail: kreydin@usc.edu).

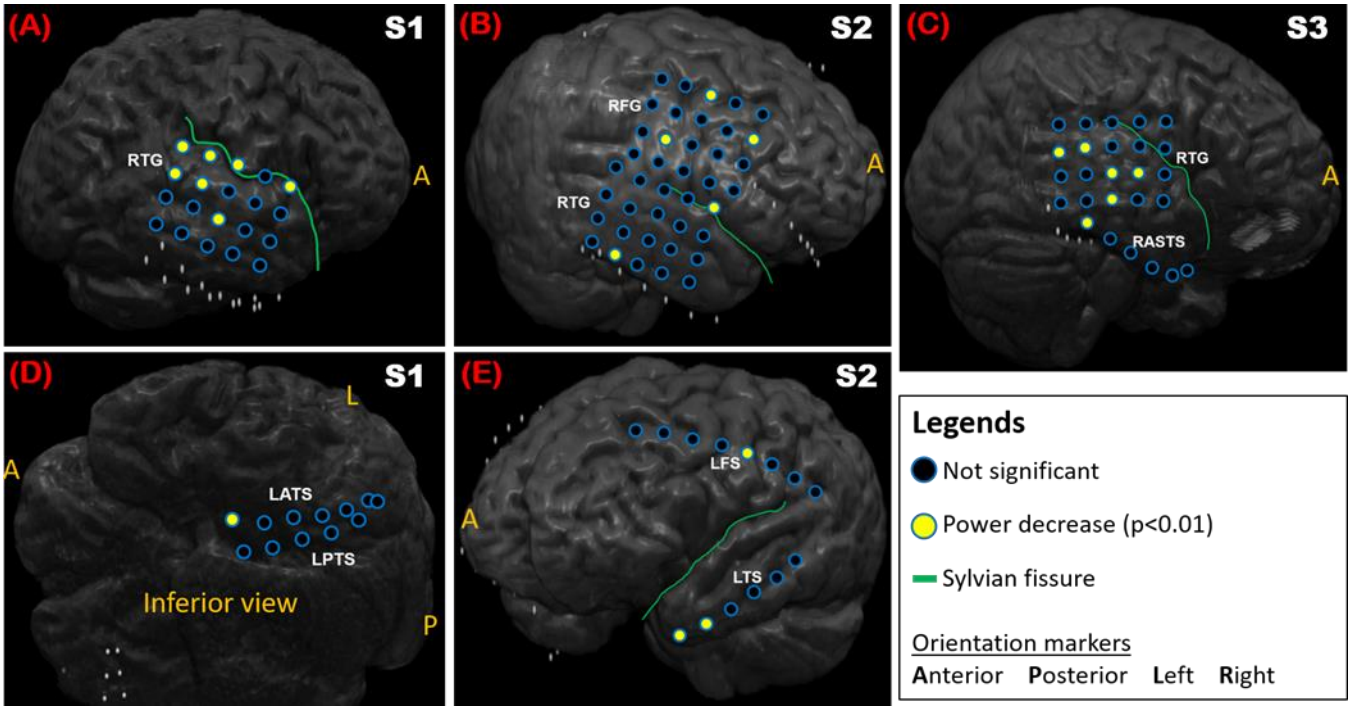


Figure 1. δ (0.1-4 Hz) activity of all subjects. All three subjects showed a decrease in δ activity in the temporal lobe. S1 and S2 additionally showed a decrease in δ activity in the frontal lobe. (A, B) S1 and S2's activities in the peri-Sylvian area. (C) S3's activity over the temporal lobe. (D) S1's activity in the inferior temporal lobe. (E) S2's activity in the inferior temporal gyrus and the frontal lobe. RTG=right temporal grid; RFG=right frontal grid; RASTS=right anterior superior temporal strip; LATS=left anterior temporal strip; LPTS=left posterior temporal strip; LFS=left frontal strip; LTS=left temporal strip.

properties of ECoG signals, we expect changes in brain activity at discrete physiological bands that are concomitant with the onset of micturition, particularly in areas mentioned in the above neuroimaging studies.

## II. Methods

In this retrospective study, video and ECoG recordings (256 Hz sampling rate) from three subjects who underwent ECoG electrode grid implantations for epilepsy surgery evaluation were reviewed. The study was approved by the Institutional Review Board of the Rancho Los Amigos National Rehabilitation Center. Micturition events were annotated after inspection of the video recordings. To determine whether there are consistent and significant differences in specific frequency patterns between the urine storage and voiding states, ECoG epochs spanning 20 s before (urine storage) and 20 s after (urine voiding) the onset of the micturition events were extracted for analysis.

The ECoG data were band-pass filtered into δ (0.1-4 Hz), θ (4-8 Hz), α (8-13 Hz), β (13-25 Hz), low-γ (25-50 Hz), and high-γ (70-110 Hz) bands. The instantaneous power of each signal was calculated by squaring the signals [10]. The band-specific ECoG power of 20-s-long urine storage and voiding epochs across all micturition events was calculated. A rank sum test was performed to compare the band-specific power during storage and voiding to determine if there were significant differences ($p<0.01$) between the two states. This was repeated across all electrodes and all subjects. For the purposes of control, two sequential 20 s epochs of ECoG signals were segmented 5 mins after each urination event. The set of the first 20 s epochs was compared to the set of the second 20 s epochs using the same approach as above. The ECoG grid electrodes that were determined to have significant band-specific power differences between storage and voiding were mapped on the subject's brain using our custom MRI co-registration technique [11]. These maps were subsequently used to interpret which brain areas and signal features are involved in urination.

## III. Results

For the three subjects monitored (S1, S2, S3), there were a total of 100 micturition events (37, 31, and 32, respectively) detected over a period of 7 days. The results are summarized in Table I. In all subjects, a significant decrease in power in the δ-band activity was observed in the temporal lobe (Fig. 1) at the onset of voiding. Notably, in both S1 and S2 this occurred around the Sylvian fissure (Fig. 1A, 1B) and in the inferior temporal lobe (Fig.1D,1E). Both subjects also exhibited a decrease in δ activity in the inferior frontal gyrus. S3 did not have electrodes implanted in the inferior temporal lobe and hence it was not possible to determine if a similar pattern occurred.

Additionally, low γ-band changes were also detected. S1 and S2 both exhibited decreased activity in the low-γ band in the inferior temporal lobe (Fig. 2A, B) during voiding. S2 furthermore displayed a decrease in low-γ activity in electrodes placed near the Sylvian fissure (Fig. 2C) in addition to the decreased δ activity already mentioned. Representative averaged signals are shown on Fig. 3. Note that there were no instances where significant ECoG power changes were found in any of the control analyses.

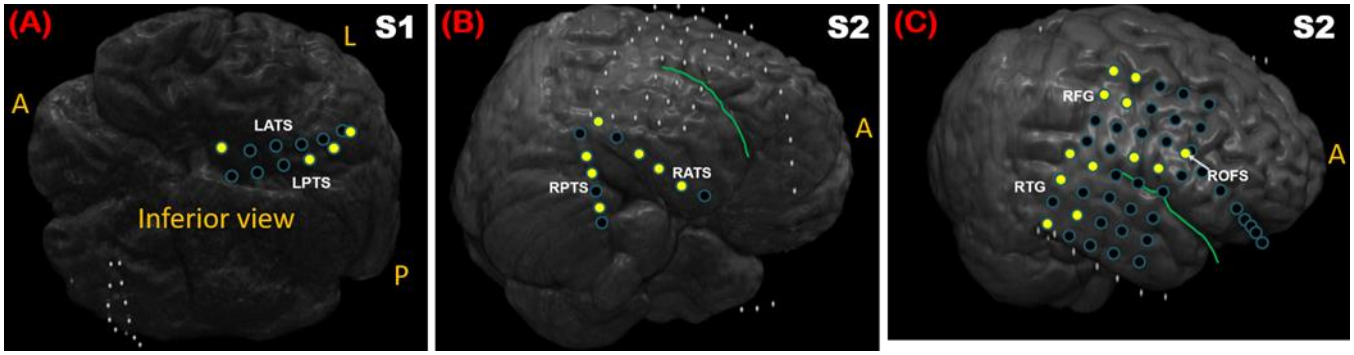


Figure 2. (A, B) Decreased low-γ activity in inferior temporal region in S1 and S2, respectively. (C) Decreased low-γ in S2 in peri-Sylvian fissure area. Additionally, there appears to be activity in the frontal and temporal lobes beyond the peri-Sylvian area. LATS=left anterior temporal strip; LPTS=left posterior temporal strip; RPTS=right posterior temporal strip; RATS=right anterior temporal strip; RFG=right frontal grid; RTG=right temporal grid; ROFS=right orbital frontal strip.

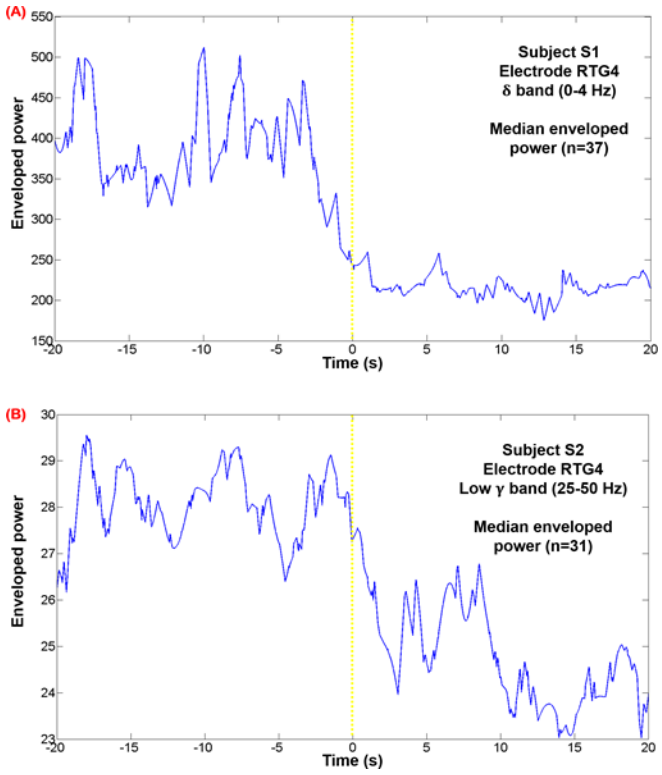


Figure 3. Representative enveloped powers of 20 seconds around micturition events for subject S1 in the δ band and subject S2 in the low γ band, averaged over all events. The yellow line at Time = 0 s indicates the onset of urination.

## IV. Discussion

To the best of our knowledge, this study is the first to characterize the electrophysiology of micturition and urinary urge in humans. Our results indicate that there were several localized changes in the electrophysiological activity of the temporal lobe and the areas immediately surrounding it during the switch between urinary storage and voiding. These spatial electrophysiological patterns are generally consistent with the phenomenon of ictal urinary urge auras (a strong desire to void before the onset of a seizure) in temporal lobe epilepsy patients [12]. However, the current study potentially provides additional insight into which specific temporal lobe areas are involved and over what physiological frequency

TABLE I. Significant Decrease in Neural Activity in Specific Bands at Onset of Micturition.

| Subject | Frontal Lobe | Temporal Lobe |
|---|---|---|
| S1 | δ | δ, Low γ |
| S2 | δ, Low γ | δ, Low γ |
| S3 | | δ |

bands. All subjects demonstrated a decrease in temporal lobe δ activity at the transition from the storage to voiding states of micturition. Notably, this pattern tended to occur in ECoG channels at the peri-Sylvian area as well as in the inferior temporal lobe. The absence of significant differences in the control analysis suggests that the physiological events found here are not due to random chance. The interpretation of these findings will be discussed in the context of bladder sensation and urination as follows.

The decrease in δ and low-γ activity over the inferior temporal gyrus is consistent with previous fMRI studies that demonstrated activation in this area during micturition [13]. These modulations may reflect activity of the uncinate fasciculus, which contain projections to and from the temporal lobe and the prefrontal cortex [14]. Given that these connections have implicated this area in decision making and social inhibition, the uncinate fasciculus can be hypothesized to play a role in the conscious control of micturition. Hence, the above brain areas and signal frequencies may represent potential targets for future technologies aiming to restore or improve volitional urination.

The decrease in δ and low-γ activity around the Sylvian fissure during urination may originate from the underlying insular cortex. While previous fMRI studies also demonstrated insula activity [15], the addition of temporal information from the ECoG signals may provide additional insights. Given that the insular cortex is recognized as a center for sensory processing of internal organs and autonomic regulation [16], it can be hypothesized that higher levels of δ and low-γ activity in the insular cortex are associated with increasingly strong sensation of fullness. More specifically, the higher peri-Sylvian δ and low-γ activity during the urine storage phase may indicate bladder fullness sensation and/or the desire to void [17]. Conversely, the significant decrease in δ and low-γ activity following the

onset of micturition can be hypothesized to indicate the cessation of bladder fullness sensation. As above, this area and its activity states can be a potential target for neural technologies aiming to restore or improve bladder sensation.

Due to the retrospective nature of the study, there are several limitations. Micturition events were annotated for analysis by visual inspection of the video recordings which resulted in a loss of temporal accuracy. Nevertheless, consistent findings that are anatomically plausible were still observed. Additionally, since the placement of ECoG grids was clinically determined, the brain area coverage varied from subject to subject. This precluded the side-by-side comparison of activity at specific brain locations across subjects. Likewise, the potential involvement of other brain areas could not be studied due to lack of coverage and artifacts due to other physiological processes cannot be excluded. Due to the retrospective analysis, controlled experiments are necessary to verify the proposed hypotheses.

Future studies that address these issues may yield essential information for the design of neural technologies that aim to improve or restore bladder voiding and sensation. Specifically, studies using controlled urodynamic measurements to determine the exact onset of urination can potentially provide higher consistency in results and address confounding factors, including changes in other autonomic functions (heart rate, breathing). Recruiting more subjects with ECoG grid placements over similar areas can help increase the evidence for the involvement of each brain area during micturition. The use of cortical stimulation can help identify the brain areas involved in the motor and sensory aspects of micturition. Finally, future studies may utilize the underlying signal features to develop neuromodulatory or neuroprosthetic approaches to restoring and/or improving bladder control and sensation in neurogenic bladder patients.

## V. Conclusion

The electrophysiology of the human brain during micturition has been poorly understood. The excellent spatial and temporal resolution of ECoG signals provides a unique opportunity to identify brain areas involved in the storage and voiding phases of micturition. Specifically, the inferior temporal lobe and the peri-Sylvian areas demonstrated significant decreases in δ and low-γ activity during micturition. The inferior temporal gyrus activity during micturition may represent the brain disengaging social inhibition to facilitate urination. On the other hand, peri-Sylvian activity may represent insular cortex processing of sensational discomfort of bladder fullness.

Micturition appears to elicit oscillatory activity from a complex set of neural networks. Since several regions of the brain are likely to be involved in the initiation of micturition, future controlled urodynamic experiments should be designed to further examine the ECoG signals underlying micturition and fully characterize these networks. This knowledge can subsequently be exploited to develop neural technologies to improve or restore bladder voiding and sensation in those with neurogenic bladder.

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