Wireless Mouse EEG Device: Novel Design for Easy Operation

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***Abstract*—Electroencephalogram (EEG) has been widely used in studies using rodent models to understand brain functions and neurological disorders. However, conventional EEG setups have limits as recording devices are bulky and tethered, causing discomfort and deviating from natural habitat conditions. To address these, we develop an innovative wireless EEG device for mice with a compact size, wireless recording via Bluetooth, and minimal invasiveness through screw mounting. The device enhances experimental setups while ensuring the well-being of the mice in a more realistic environment facilitating easier translation to human studies. In an experimental setting involving induced seizures, EEG signals were recorded and analyzed to discern differences across epilepsy phases in both anesthetized and awake stages. This device holds promise to revolutionize EEG research using mice, bridging the gap between laboratory conditions and real-world scenarios, thus advancing our understanding of neurological phenomena.**

***Index Terms*—Electroencephalogram, Environment, Epilepsy, Mouse, Real-time Recording, Wireless Device**

I. INTRODUCTION

Electroencephalogram (EEG) is a noninvasive technique widely used to assess the electrical activity of the brain. EEG has been used in a wide range of clinical applications, which is critical in addressing the urgent need to understand the cause and effect of neurological diseases for effective diagnosis and treatment [1]. Despite the advantages of EEG for real-time monitoring, such as its cost-effectiveness and low dependence on large equipment, EEG presents certain challenges, such as its non-stationary characteristics and the devices used for recording are very responsive to ambient noise [2].

The primary objective of this study is focused on designing and advancing a novel wireless electroencephalogram (EEG) device for mice, with the aim of transforming neuroscience research involving rodents. Unlike conventional wired and tedious setups used to study model organisms [3], [4], this innovative device, minimizes invasiveness through secure screw-based attachments on the skull, features a compact size through efficient hardware design, and enables wireless recording using low-power Bluetooth communication.

Traditionally, mouse EEG acquisition systems have been constrained by fixed configurations, necessitating controlled environments, often involving anesthesia or caging to restrict movement due to tethering [5], [6]. These would make the collected data extrinsic; thus raising questions about the relevance

This research was funded by NSF NCS #1926818 to Hung Cao.

of studies. The introduction of this wireless EEG device marks a substantial departure from these limitations [7] facilitating the observation of neural activity during various behaviors and interactions, providing valuable insights into the dynamics of rodent brains in their natural environments. Furthermore, the mounting method involving secure screws strikes a balance between invasiveness and precision. The system is mounted on the mouse solely with screws, eliminating any use of cables or invasive techniques that could be harmful to the subject.

By ensuring minimal invasiveness and stability in the electrode placement, this device facilitates accurate and reliable neural recordings. The wireless configuration, coupled with this secure yet minimally invasive attachment and compact size, not only prioritizes the welfare of the research subjects but also ensures the integrity of the recorded data.

II. ENGINEERING METHODOLOGY

The following section outlines the technical details of the wireless mouse EEG device, including its architecture and design.

The basic functionality of the device is streamlined into a series of steps, each of which contributes to the overall efficiency and reliability of the system. Starting with EEG signal acquisition, the device uses electrodes made of 303 stainless steel attached firmly to the mouse skull at carefully chosen points depending on the objective of the experiments being performed. In this study, we utilized this cable-free system, which not only simplifies the setup process but also reduces discomfort to the mouse. Following signal acquisition, EEG signals are amplified with a gain of 100, along with noise reduction facilitated by a High Pass Filter (HPF). The analog signals are then meticulously converted to digital format using a high-resolution 24-bit analog-to-digital converter (ADC). The converter also includes a notch filter at 60 Hz for power line noise. This process of conversion, further enhanced by an additional gain ranging from 1 to 128, results in a remarkable total system gain ranging from 100 to 12800. Such precision in signal processing ensures the integrity of the recorded neural data. Then, the digital signals are transmitted to the nRF52832 Nordic microcontroller via the Serial Peripheral Interface (SPI) communication protocol. The microcontroller, as the central processing unit of the system, first, configures the ADC to the desired parameters and then efficiently organizes the data into packets and prepares them for transmission via the Bluetooth Low Energy (BLE) protocol to a smartphone. An Android app has been designed for real-time data acquisition using Bluetooth, which is capable of plotting the multi-channel recorded EEG data in real-time and storing them for further processing and analysis.

Fig. 1 shows the device diagrams and the experiment setup. Fig. 1.b illustrates the three-dimensional model of the entire device, which encompasses the battery powering the entire system and the physical casing enclosing the device. The BLE board contains the microcontroller and connects to the EEG board which is responsible for the acquisition of EEG signals and the processing and conversion of the data. The complete

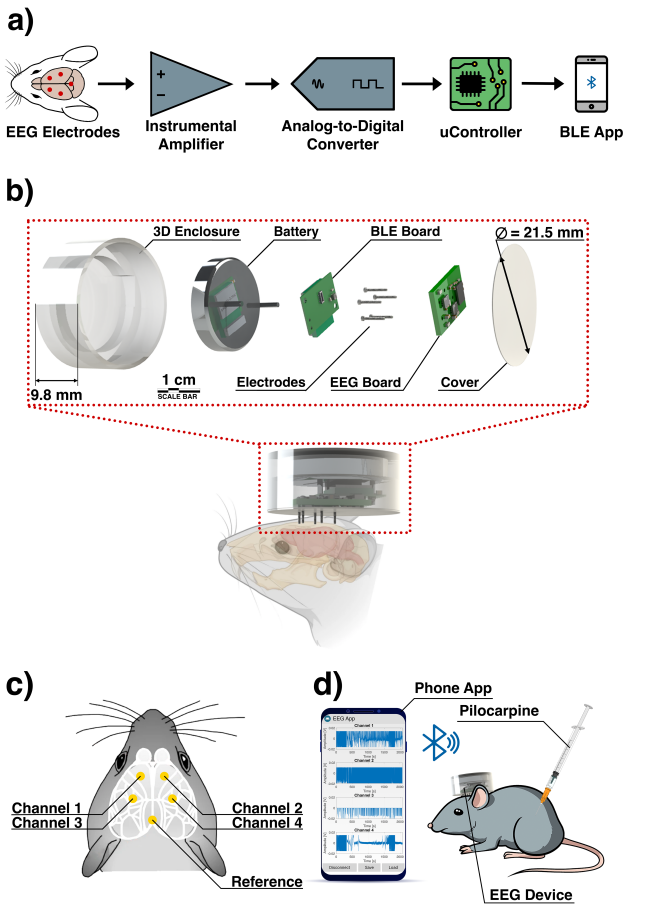

Fig. 1. (a) Wireless EEG recording system block diagram. (b) 3D Model rendering of the Wireless EEG recording system. (c) Electrode placement position for EEG recording. (d) Experimental setup.

device is encapsulated and protected. The meticulous design of the device extends to its physical dimensions. The entire system, including the integrated battery, features a compact size, measuring just 21.5 mm in diameter and 9.8 mm in height, with a minimum mass of 3.79 grams. This reduced size is essential and is achieved through the use of 6-layer manufacturing technology and small PCB footprints. This measure aims not only to alleviate discomfort for the mice but also to enhance the usability and maneuverability of the experimental environment.

III. EXPERIMENT

A. Device Implantation

The experimental setup involved precise positioning of the EEG electrodes through drilled holes in the mouse's skull, as illustrated in Fig. 1.c. The EEG device was implanted in 5-6-month-old C57BL/6 mice for EEG recording. Mice were housed in an environment with temperature maintained between 21 – 23 °C and humidity between 40% - 70%. Mice had free access to food and water. All the animal experiments were approved by the Institutional Animal Care and Use Committee of the University of California, Irvine, and carried

out following protocol #AUP-22-163 and the Guide for the Care and Use of Laboratory Animals. For surgery, mice were anesthetized with 2-3% isoflurane and placed on a stereotaxic frame. A scalp incision was made along the middle line of the head, then holes were drilled in the skull above the hippocampus and motor cortex areas using a 0.5-mm bur. The coordinates (relative to the bregma) are AP-2.3 mm, L±1.6 mm for the hippocampus, and AP-0.1 mm, L±1.5 mm for the motor cortex. The reference electrode was placed over the cerebellum at AP-5.6 mm, L=0mm relative to the bregma. The EEG device with electrodes was placed on the skull by inserting the electrodes in the holes to target the brain areas to be recorded. Then the EEG device was fixed on the skull using dental cement. This meticulous electrode placement was crucial for capturing accurate neural activity while maintaining the animal's comfort and well-being.

B. Induction of Seizure and EEG Recording

Mice were placed individually in their cages and seizures were induced by intraperitoneal (i.p.) injection of pilocarpine at a dose of 350 mg/kg. Scopolamine was i.p. injected at a dose of 1 mg/kg 30 min before pilocarpine to reduce any peripheral effects caused by pilocarpine. After the device was firmly mounted and connected to the recording app, pilocarpine was injected and EEG was monitored until seizure behavior and status epileptic EEG appeared (about 1 h). The complete setup, depicted in Fig. 1.d, includes the anesthetized mouse, the wireless EEG device, and a dedicated mobile application. The device, with its electrodes securely attached to the designated positions on the skull, was seamlessly connected to the mobile app, establishing a reliable communication link. This integration enabled real-time data transmission and visualization on the mobile application, allowing researchers to monitor and analyze the EEG signals instantaneously.

C. Data Analysis

The raw EEG data sampled at 280 Hz per channel obtained from the wireless EEG device were processed using computational techniques in Matlab. To enhance the clarity of the data, Band Pass Filters (BPF) were meticulously applied to extract noise that could be coupled during recording and to preserve the frequencies of interest. This is done using a 6th-order Butterworth filter with the lower and upper cutoff frequencies at 1 Hz and 100 Hz respectively. Subsequently, segments from the filtered data were extracted to distinguish the control signal and the epileptic signal. The Short-Time Fourier Transform (STFT) was computed on each EEG segment of interest using a hamming window of size 1024 and an overlap of 25%. The resulting spectrograms were obtained with a frequency range between 1 Hz and 100 Hz. The analysis focused on extracting the frequency components within this range providing insights into the time-varying spectral characteristics of the EEG signal. Finally, the Power Spectral Densities (PSD) of the EEG segments were computed using the Pwelch function.

IV. RESULTS AND DISCUSSION

A significant innovation lies in the compact and user-friendly design of the device. Unlike conventional approaches that involve unwieldy wiring that connects electrodes to the acquisition system, our device ingeniously employs the electrodes themselves as attachment points. This innovative approach not only reduces the overall size and complexity of the installation but also eliminates the discomfort associated with extraneous wires, thus ensuring a stress-free environment for the research subject.

Fig. 2(a) illustrates the comparison of filtered EEG data across the entire experimental timeline, focusing on three distinct segments: Control, Anesthetized Seizures, and Awake Seizures were selected for further analysis. The Control segment denotes EEG data without epileptic activity, serving as a baseline for comparison. Anesthetized Seizures represent the segment marked by initial seizures as the pilocarpine takes effect and when the mouse is anesthetized. Finally, Awake Seizures signifies the segment following the removal of anesthesia from the mouse. Initial high-amplitude signals in the EEG signal stem from muscle movements in the mouse.

In the Control segment (Fig. 2(b)), the EEG displays low amplitude without any seizure spikes as expected, indicating that the pilocarpine has not yet begun to take effect. Subsequently, in the Anesthetized Seizures segment (Fig. 2(c)), noticeable seizure spikes with higher amplitude than the baseline are observed, with distinct intervals between them. This pattern aligns with early epilepsy onset, where seizure frequency increases over time. Lastly, during the Awake Seizures segment (Fig. 2(a)), the mouse was conscious and experienced more frequent seizures.

Fig. 2(e) plots the spectrogram of the Control segment which exhibits low power and a homogeneous spectral pattern indicating an absence of seizure activity. On the other hand, in the Anesthetized Seizures segment (Fig. 2(f)), there is an increase of power at higher frequencies, precisely where seizure spikes occur. Then, the Awake Seizures spectrogram segment (Fig. 2(g)) demonstrates elevated power across the entire spectrum, particularly in higher frequencies corresponding to increased spike density. These spectrograms utilize a consistent color bar to facilitate visual comparison across the different plots.

Fig. 2(h) represents the EEG Power Spectral Density (PSD), which provides an analysis of the power distribution across different frequencies, offering insights into the relative strength of neural oscillations. It can be observed that the Control segment exhibits lower power distribution across all frequency ranges, especially at lower frequencies. Conversely, the Anesthetized Seizures and Awake Seizures segments display similar power distribution across the entire spectral range, notably higher than that of the Control segment.

The processed EEG data presented in Fig. 2 clearly delineates corresponding events observed during the experiment. The precision of the EEG signals mirrors the neurological changes precisely at the points where these events occur. This

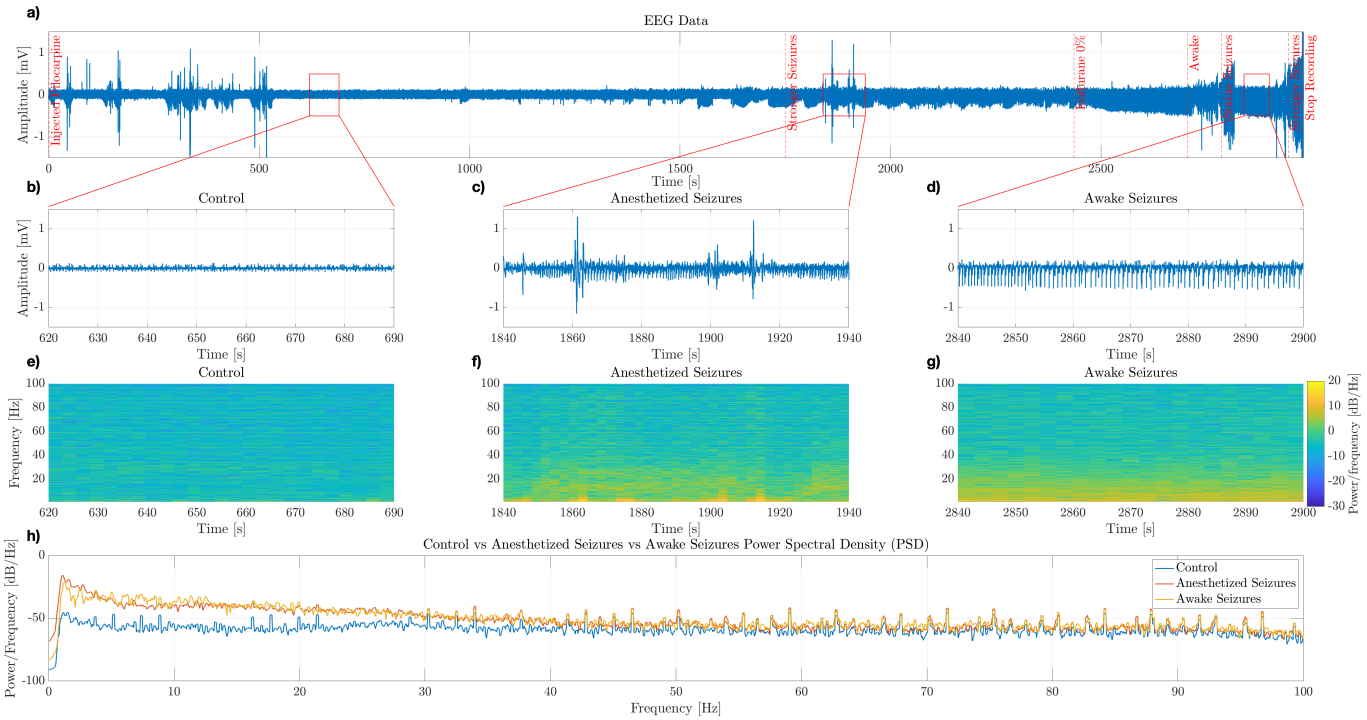

Fig. 2. EEG Data Analysis. (a): Filtered EEG Data. (b), (c), and (d): EEG signals from Control, Anesthetized Seizures, and Awake Seizures segments, respectively. (e), (f), and (g): EEG Spectrograms of the respective segments. (h): EEG Power Spectral Density of the respective segments.

level of accuracy not only validates the efficacy of the wireless mouse EEG device but also underscores its potential as a robust tool for studying real-time neural dynamics in response to controlled stimuli.

V. CONCLUSION AND FUTURE SCOPE

In conclusion, this study introduces a novel wireless EEG device designed specifically for mice, diverging from conventional wired configurations that constrain movement and induce stress in model organisms. This device offers minimal invasive attachments, compact size, and wireless recording capabilities, enabling rodents to move freely. The results of this study demonstrate the efficacy and versatility of the wireless EEG device. Analysis of filtered EEG data reveals distinct patterns across experimental segments, notably detecting seizure activity during both the Anesthetized and Awake phases, highlighting the device's ability to capture real-time neural dynamics accurately in anesthesia and conscious states. By providing researchers with a tool capable of real-time monitoring in natural environments, the wireless mouse EEG device opens avenues for a deeper understanding of neural processes and neurological disorders in rodent models. Furthermore, a promising advancement involves integrating neurotransmitter sensors with a potentiostat system to remotely measure crucial neurotransmitters like L-glutamate and GABA alongside EEG signals [8]. This integrated system enables real-time monitoring of both electrical activity and neurotransmitter fluctuations, particularly in awake animals, eliminating confounding factors related to anesthesia for a more naturalistic representation of brain activity. In conclusion, this study underscores the transformative potential of this wireless EEG device in advancing neuroscience research, offering researchers a reliable platform for investigating complex neural phenomena in rodents.

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