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INTEGRATING CORTEC BRAIN INTERCHANGE DEVICE AND BCI2000 WITH A CLOUD INTERFACE

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ABSTRACT: Emerging brain-computer interface (BCI) systems may aim to develop invasive implantable systems to restore functionality in people with paralytic disabilities and to deliver adaptive brain stimulation (ABS) to treat severe neurological disorders. A key characteristic of next-generation implantable systems will be their capability to record extended periods of local field potential (LFP) data. Timely transfer of the recorded LFPs to the clinical team is crucial for monitoring the implanted system's reliability, safety and to dynamically enhance BCI and ABS applications in response to changing brain states. Our team is developing a comprehensive therapeutic BCI ecosystem that combines the Cortec BrainInterchange hardware with the BCI2000 software environment. We have designed an architecture that seamlessly integrates recorded neural signals with device performance metrics, delivering these insights to the care team through a cloud-based interface. In order for future centers-of-excellence to be able to deliver care with clinical BCIs, closed-loop algorithms will need be able to be dynamically updated without physically interacting with the patient for each adjustment. Our BCI ecosystem is currently being tested with canine subjects, and this manuscript describes how device function (impedance measures) and brain data (LFP signals) were measured daily for an 8 week period following implantation through the cloud interface. Cloud based data synchronization for implantable brain technologies is essential for dynamic re-calibration of reliable and safe BCI and ABS therapies in the clinical setting.

INTRODUCTION

Recent advancements in the field of implantable neurotechnology have enabled continuous streaming of local field potential data (LFP) spanning years, mainly thanks to rechargeable batteries. Some applications of such devices focus on seizure monitoring and optimizing epilepsy treatment [1–5], while others focus on brain-computer interface (BCI) applications for people with paralytic disabilities [6].

The CorTec Brain Inter-Change (BIC) device aims to develop an advanced ecosystem with BCI2000 to facilitate chronic data recording to restore functionality in people with paralytic disabilities [6] as well as to deliver adaptive brain stimulation (ABS) as a treatment for severe neurological disorders [7]. Initial developments have demonstrated the utility of such a system and its capability to record clinically relevant data [7, 8].

Worrell and his team have demonstrated the utility of an implantable system for continuous LFP streaming to track primary markers of epilepsy and its comorbidities, including interictal epileptiform discharges, seizures, sleep, cognition, and mood [3, 5, 9–11].

The transfer of LFP data recorded from implantable neurostimulators to the clinical team is a critical task enabling remote supervision of autonomous implantable systems and facilitating the improvement of algorithms for BCI and ABS applications [9].

This work describes progress in the development of an ecosystem for BCI and adaptive neuromodulation in humans by documenting efforts to integrate the CorTec BrainInterchange (BIC) device with BCI2000 [12] and a cloud interface to transfer LFP data from a computer interacting with the implanted device into a research storage compliant with BIDS data structure [13].

MATERIALS AND METHODS

Recording System: The Brain Interchange (BIC) unit (CorTec GmbH) is an implantable battery-less research system with customizable leads, offering up to 32 channels and inductive powering. BIC is capable of simultaneous recording from all 32 channels with a 1 kHz sampling rate and generating stimulation pulses with a maximum frequency of 200 Hz, an amplitude of 6.12 mA, and

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a pulse width of up to 2.5 ms. The BIC unit consists of three pieces (Fig. 1): the implanted device, the headpiece for inductive powering of the implanted device, and the communication unit [8].

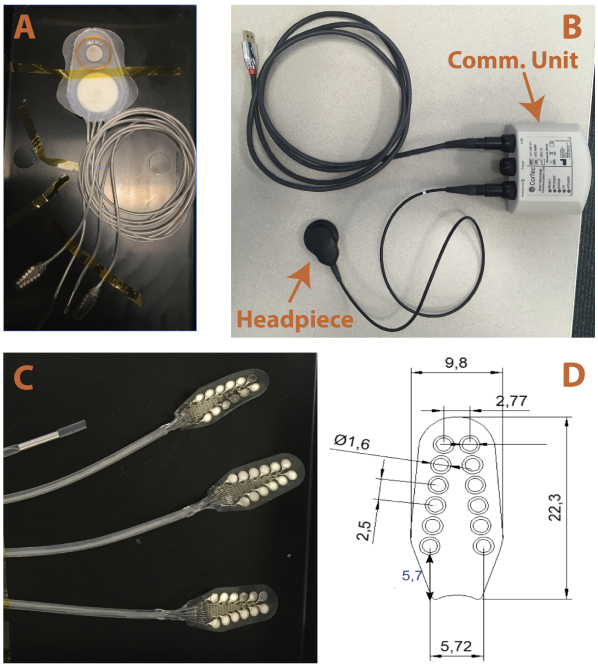

Figure 1: **Experimental CorTec Brain Interchange implantable system.** **A)** The Brain Interchange device in 3 grid electrode configurations with an additional ground electrode. **B)** The headpiece connects to the device magnetically and inductively powers the brain implant. The communication unit is plugged into a Windows computer and facilitates wireless communication and real-time data streaming from the implanted device. **C)** The configuration of the implanted electrodes. **D)** Electrode dimensions for the electrode with 12 contacts.

Cloud Synchronization and Data Storage: Electrophysiology data recorded using the implanted BIC device and BCI2000 ecosystem [12] are manually stored on the Recording Windows Computer in the "Drop directory". This data is already organized in the subject- and session-oriented file scheme compliantly with the BIDS data structure [13]. Data is automatically transferred over to a cloud storage platform and further synchronized to its final destination, which in our implementation is a research Linux server. The data is automatically converted into MEF3 format and stored in BIDS format with corresponding annotation files (Figure 2). The original raw data are preserved as well in the *sourcedata* folder.

Ethical Statement: This research was conducted under Mayo Clinic IACUC protocol A00001713. According to the State of Minnesota statute 135A.191, the canines can be made available for adoption if for any reason the research were to be discontinued. The intent of this animal research is to test and develop a platform for novel human therapeutics.

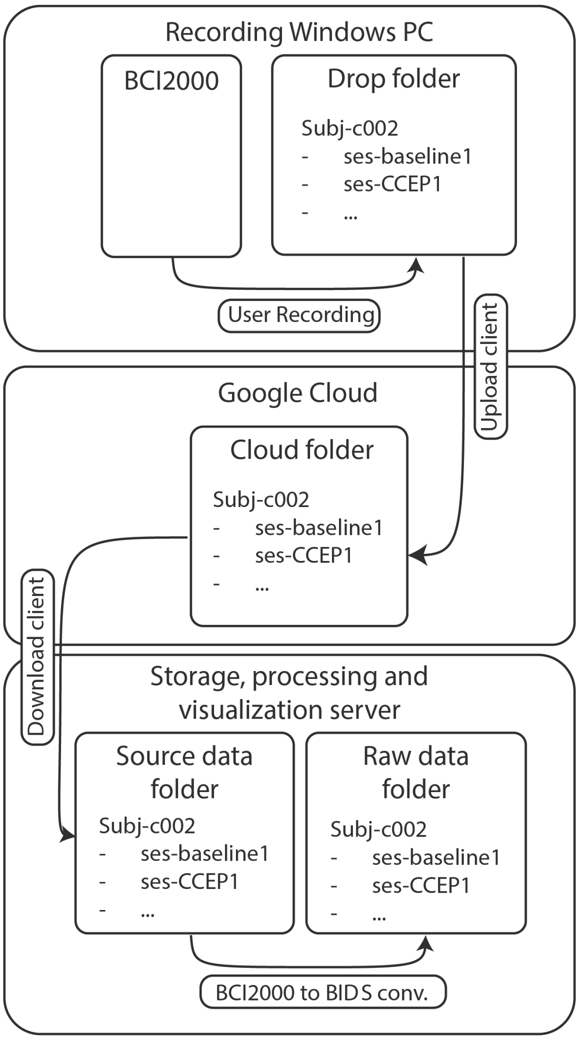

Figure 2: **Data transfer flowchart.** The developed data synchronization system automatically transfers and converts files generated by BCI2000 on the Recording Windows Personal Computer (PC). Brain signals are recorded using the BCI2000 platform connected to the implanted CorTec BIC system. The recorded data is stored in a *"Drop Folder"* in a subject- and session-oriented storage scheme designed for seamless conversion into the BIDS data format [13]. The data is automatically transferred to a Google Cloud storage as a data transfer platform and subsequently converted into MEF3 format and stored compliantly with the BIDS data organization scheme. The example in this figure represents a scheme for one subject *"c002"* with two sessions called *"baseline1"* and *"CCEP1"*.

Subject: Canines present a promising translational model for human implantable systems [1, 10]. Dogs share an evolutionary history with humans and are a promising model for studying behavior, sleep, and neurological disorders [14, 15]. Moreover, canines are large enough to accommodate human-sized electrodes and devices, and canine neurological disorders share features with humans [9, 10].

One adult female intact beagle was housed on a 12/12 light cycle and fed approximately two cups of Lab Diet 5L18, with water provided ad libitum. The animal was housed in temperature-controlled rooms with elevated floors that met all size, material, and sanitation require-

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ments according to the Guide for the Care and Use of Laboratory Animals and the Animal Welfare Act. The animal was provided with mats and daily enrichment through assorted treats, chew toys, and human interaction. Animals were socially housed and were assessed daily by a team of veterinarians.

Implant Surgery: Pre-surgical magnetic resonance imaging (MRI) - T1-MPRAGE and computed tomography (CT) were utilized to segment brain and skull anatomy. MRI imaging was coregistered to an existing stereotactic atlas of a canine brain [16]. A full-scale replica was 3D-printed using the MRI and CT scans (Figure 3). The 3D brain model aided in pre-surgical planning. The canine was implanted with a research 3-lead CorTec BIC device. The surgery was performed using a stereotactic targeting software, BrainLab, with a custom-made stereotactic frame [10, 17]. Grid electrodes were placed targeting primarily the Sensorimotor, Occipital, and Temporal cortex (Figure 4).

LFP signals were recorded during the surgery under anesthesia and while the canine was waking up to assess the signal quality. Post-surgical CT was utilized to detect individual electrodes.

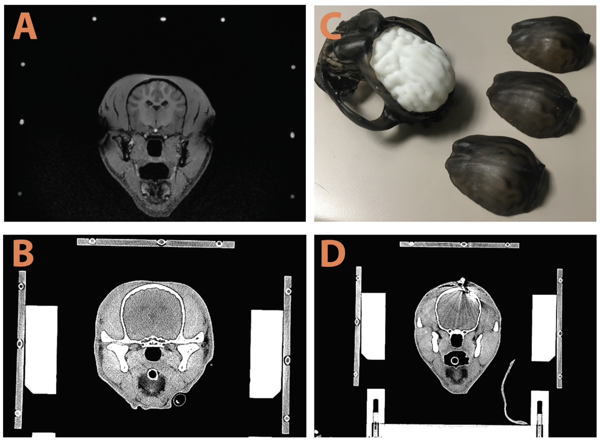

Figure 3: **Preoperative imaging and 3D print.** **A)** Pre-operative Magnetic Resonance Imaging (MRI) T1-MPRAGE Sequence used for developing a 3D brain model and stereotactic targeting. **B)** Pre-operative Computed Tomography (CT) used for developing a 3D brain model and stereotactic targeting. **C)** A full-scale 3D-printed model aiding in surgery planning. **D)** Post-operative CT with distinct metal artifacts caused by the implanted electrodes.

Long-term Recording Protocol: A recording protocol was designed to validate the recording stability of the implanted BIC system. The impedance of all electrodes was measured daily along with a set of three 3-minute recordings, each with a different reference electrode.

Reproducible Research - Data & Code Sharing: The authors are committed to sharing data and code to facilitate reproducible research. All codes utilized and developed within this project beyond the BCI2000 ecosystem are publicly available on GitHub as Python software packages: *Behavioral State Analysis Toolbox (BEST)* (`https://github.com/bnelair/best_toolbox`) and *Mef Tools* (`https://github.com/bnelair/mef_tools`). The data were published as a dataset called *Intracranial recordings using BCI2000 and the CorTec BrainInterchange* on OpenNeuro [18].

RESULTS

We integrated the CorTec BIC system with BCI2000 with a cloud data synchronization system [1, 12]. The developed data synchronization system automatically transfers LFP recordings from the acquisition computer running BCI2000 to a cloud environment and further to the hospital. We demonstrated that such a system can serve for long-term monitoring of the technical parameters of the implanted system, as well as the LFP recordings.

The implanted BIC system has demonstrated sensitivity to LFP changes related to different behavioral states (anesthesia during surgery vs. wakefulness). LFP changes were dominant in lower frequencies below 25 Hz (anesthesia vs. wakefulness: > 30 dB vs. 20 dB) (Fig. 4). Subsequently, we monitored the dog for 40 days after the implant surgery using 3-minute LFP recordings every day along with collecting impedance measurements. The electrical impedance and LFP power stabilized after 20 recording days, which corresponded to an increase in the signal power (Fig. 5). We also identified 4 channels with either permanently high impedance (>5 $k\Omega$) or sudden impedance changes. These channels were excluded from subsequent analysis.

DISCUSSION

Multiple chronic implantable BCI systems are currently being developed with the aim of restoring functionality in paralyzed people and providing ABS for neurological conditions such as epilepsy, movement disorders, stroke, and others [1, 7].

LFPs recorded by an implantable system are a key data source in assessing the system performance and reliability while patients live their lives in a home environment. The performance of any implantable system in BCI or adaptive DBS applications might be significantly impacted by medication-induced LFP changes or high electrode impedance caused by compromised channel integrity. These factors can jeopardize the performance of detection algorithms crucial in BCI and responsive DBS applications.

Timely delivery of LFP signals and technical health information from the implanted systems from a patient home environment to a clinical team with minimal patient and physician effort is, therefore, an important task to ensure continuous safety and efficacy o f the

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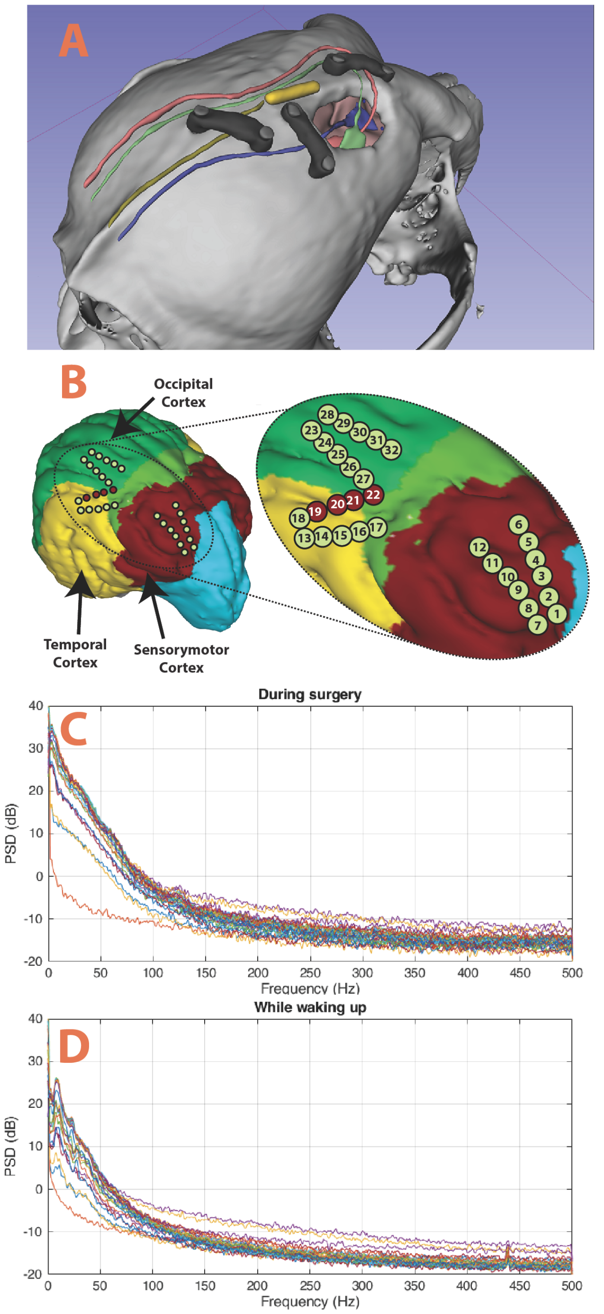

Figure 4: **Post-surgical rendering and LFP recording.** **A)** A surface rendering of the leads secured to the skull. **B)** A visualization of all 32 channels distributed among 3 leads placed over Sensorimotor Cortex, Occipital Cortex and Temporal Cortex [16]. Red color symbolizes electrodes with impedance > 5 $k\Omega$ at any time of chronic recording. **C)** A power spectrum density (PSD) of the iEEG signals recorded during deep anesthesia. **D)** iEEG PSD for the canine waking up from the anesthesia manifests different power in low frequencies compared to deep anesthesia.

implantable system. Data of interest can include LFP recordings, electrode impedance, battery level, amount of delivered stimulation, and any other data that might be beneficial to monitor [1, 2].

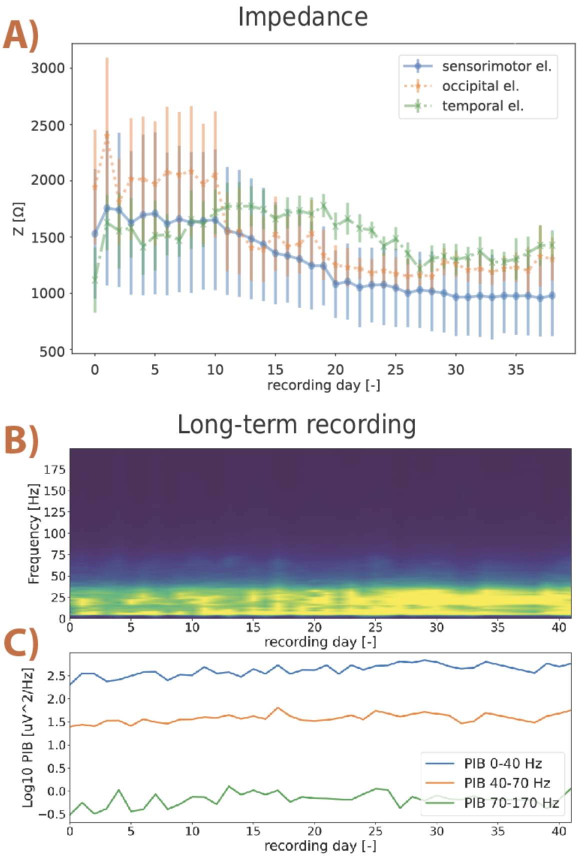

Figure 5: **Impedance and recording demonstrated over the first 40 recording days.** **A)** Impedance average calculated over all channels for each implanted lead (sensorimotor cortex, occipital cortex, and temporal cortex) decreases and stabilizes over the first 10-20 days after the implant. **B)** Power spectrum density mildly increases over time corresponding to the impedance decrease. **C)** Gradual power increase demonstrated using power in the band (PIB) visualization for bands 0-40 Hz, 40-70 Hz, and 70-170 Hz.

Here, we integrated an experimental BCI system (CorTec BIC) with an open-source software platform for non-commercial use, BCI2000, which integrates multiple recording and stimulating systems to record, process data, and stimulate using a single platform. Recorded data is automatically synchronized over a cloud interface into a BIDS structured data storage. We demonstrated the feasibility of such a system in one canine implanted with CorTec BIC that was monitored daily for 40 days after the implant surgery. The utility of the proposed system and the need for the collection of technical and LFP data from implanted devices were demonstrated by revealing and identifying faulty channels and monitoring changes in the signal power related to impedance stabilization after the implant.

The cloud-based interface allowed us, in simulation of a remote interaction, to identify sources of packet loss, including A) sensitivity of the Communication Unit orientation towards the implant with a data dropout rate ranging from 1-20%, depending on orientation; B) Interference with surrounding wireless devices. Both of these

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shortcomings can be overcome by careful experiment design and/or by implementing a multi-directional antenna in the Communication Unit. Initial experiments show automatic reconnecting of the BCI2000 to the implanted BIC can significantly improve data transmission. The BIC is powered inductively, and the headpiece magnet can be a point of connection loss during extended periods of time, exacerbated by animal movement. Notably, the canine represents a particularly challenging subject due to the range and frequency of movements. The system can easily be improved but will likely be adequate for applications in people with restricted movement, e.g., the locked-in syndrome [6].

CONCLUSION

BCI systems have the potential to improve the quality of life for many patients with neurological disease, but therapeutic interventions will require scalability beyond the attention of technical experts directly interacting with the patient. Cloud-based interfaces like the novel one that we demonstrate here, will enable trained technicians to interact with patient devices from a distance. We demonstrate regular interaction with our nascent ecosystem for eight consecutive weeks post implant, without disruption.

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