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Development of High Resolution, Multiplexed Electrode Arrays: Opportunities and Challenges

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***Abstract*— More than one third of the world's 60 million people with epilepsy have seizures that cannot be controlled by medication. Some of these individuals may be candidates for surgical removal of brain regions that generate seizures, but the chance of being seizure free after epilepsy surgery is as low as 35% in many patients**[1]**. Even when surgery is successful, patients risk neurological deficits like memory loss and speech difficulties. The need for new treatments is clear.**

A central barrier to better treatments for epilepsy is technological: we do not have devices capable of interfacing with the brain with small enough electrodes over large enough regions to map epileptic networks in sufficient detail to enable treatment. Our collaborative group has developed new implantable brain devices to address this challenge[2]**. Our devices, made from flexible silicon nanoribbons, can record from these very small brain regions, with electrodes ½ millimeter apart or less, and can be scaled up to clinically useful sizes, on the order of 64 cm^2. They consist of thousands of individually controllable microelectrodes.**

I. Introduction

Currently, all clinical devices that interface electronics with the body use passive electrodes and require each electrode to be individually wired and connected to remote electronics - a design that has changed little since the first cardiac pacemaker implant over half a century ago. We have developed a new generation of implantable devices that use active, flexible electronics to interface with the brain at 400 times higher spatial resolution than today's clinical devices[2]. This technology opens a new window into understanding brain function, and potentially enables new methods for localizing and treating neurologic disorders.

Exciting new developments in translational research demonstrate that submillimeter resolution reveals neurophysiology not visible using electrodes with standard clinical resolution [3],[4]. Electrode arrays with submillimeter resolution may also dramatically improve the capability of brain computer interface systems to decode motor signals [5–10] and spoken words [11].

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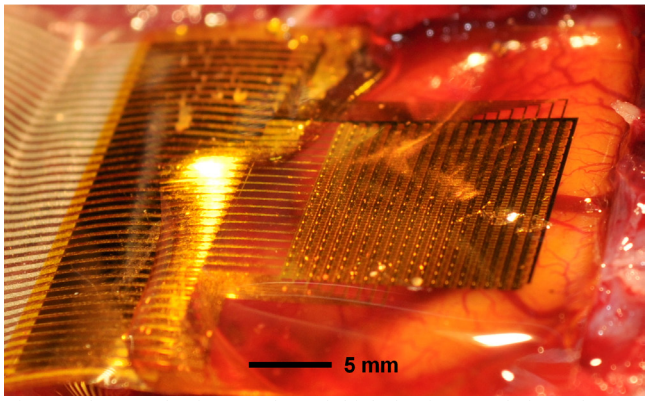

Fig. 1. Photograph of a 360 channel, high density neural electrode array used in a feline model of epilepsy. The electrode array is placed on the surface of visual cortex. The electrode size and spacing is 300 μm x 300 μm and 500 μm, respectively.

Unfortunately, it is impossible to build a high-resolution (< 1 mm) interface over broad regions (8 cm × 8 cm) of the brain using current technology, as an electrode array with thousands of passive contacts would require thousands of wires to be individually connected. To overcome this limitation, we have developed new implantable electrode array technology that incorporates active, flexible silicon electronics (Fig. 1).

We have demonstrated extremely flexible arrays of 360 recording electrodes that integrate an amplifier and multiplexer directly under each electrode in a sheet of thin polyimide. These electrode arrays can sample micro-electrocorticographic (μECoG) signals from the surface of the brain at high temporal (> 10 kHz/channel) and high spatial resolution (< 500 μm electrode spacing), while requiring only a few (e.g. 36) wires to be connected.

II. Opportunities

The development of this technology offers opportunities for diagnostic and therapeutic instruments that can be chronically implanted in humans, as well as tools that can accelerate research in systems neuroscience. Such tools may yield fresh insights into and offer new treatment options for many neurologic disorders, as well as improve the performance and capabilities of neuroprostethic systems, cochlear implants, retinal implants, deep brain stimulation systems, and cardiac pacemakers and defibrillators. At the core of the design of this device is a simple "unit cell" design that is tiled and repeated to cover the surface of the desired array size. The number, spacing and size of the active electrodes can be easily changed and fabricated quickly. In this way, the same basic design of thin sheets of electrodes

can be adapted for use in varied body locations and applications.

III. Challenges

The vast quantities of data produced by µECoG electrode arrays present new challenges for wireless data transmission, storage and analysis. As these arrays are scaled from 360 channels to over 6,400 channels, the amount of data produced will dramatically increase. As an example, an electrode array with 6,400 channels, each sampled at 2 kS/s and 24-bits per sample will require over 300 Mbps of wireless bandwidth and produce over 128 GB of data per hour.

To combat this increase in bandwidth, we are developing power-efficient methods of spatiotemporal data compression. These methods [12], adapted from well-established image and video compression techniques, exploit spatial and temporal correlations in the high-resolution data to provide significant reductions in data size. We are also experimenting with relatively newer approaches like compressed sensing [13], [14], which may eventually permit the acquisition of certain classes of neural data at sub-Nyquist rates. Preliminary work suggests that high frequency (100-500 Hz) oscillations, for example, may be amenable to compressed sensing (Fig. 2).

IV. Conclusion

We believe these technological developments will enable new approaches to detecting, classifying, and modulating high frequency oscillations (HFOs), microseizures and interictal spikes with fine detail over large areas of brain. We believe that only by interacting with the brain at fine spatial scales similar to the natural functional scale of the brain, and with coverage that can capture the full extent of the distributed nature of activity in the brain, will researchers and clinicians be able to begin to unravel the complicated, micro-scale phenomena that trigger seizures, and develop highly effective micro-scale treatments to prevent them.

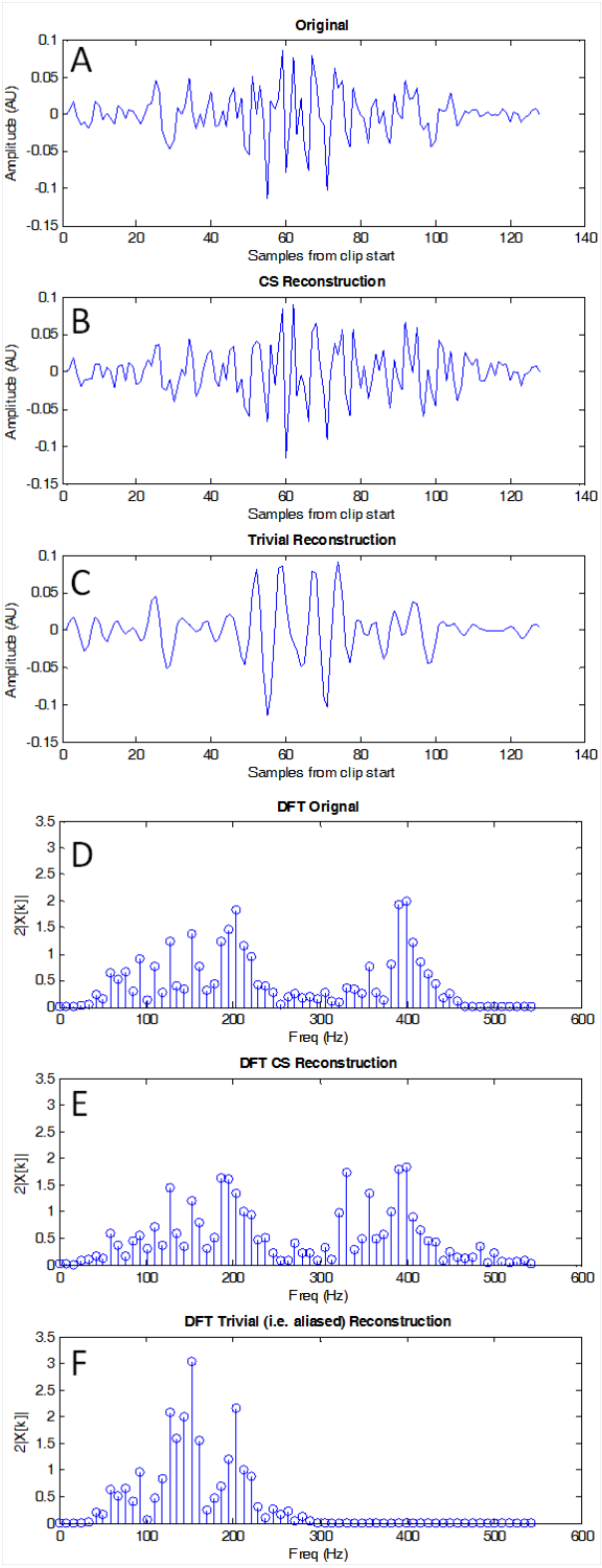

Fig. 2. Compressive sampling (CS) of human high-frequency oscillations (HFOs). Time (A,B,C) and frequency (D,E,F) domain representations of an HFO event "sampled" at approximately Nyquist (A,D) and half-Nyquist (B,E and C,F) rates. (B,E) show the reconstruction from CS samples using L1 minimization. (C,F) show the reconstruction from samples obtained by doing naïve downsampling (i.e. without lowpass filtering) followed by Shannon-like interpolation. The expected aliasing is seen in (C,F) while (B,E) is a more faithful representation of the original signal (A,D).

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