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Review

Proceedings of the Second International Workshop on Advances in Electrocorticography

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ABSTRACT

The Second International Workshop on Advances in Electrocorticography (ECoG) was convened in San Diego, CA, USA, on November 11–12, 2010. Between this meeting and the inaugural 2009 event, a much clearer picture has been emerging of cortical ECoG physiology and its relationship to local field potentials and single-cell recordings. Innovations in material engineering are advancing the goal of a stable long-term recording interface. Continued evolution of ECoG-driven brain–computer interface technology is determining innovation in neuroprosthetics. Improvements in instrumentation and statistical methodologies continue to elucidate ECoG correlates of normal human function as well as the ictal state. This proceedings document summarizes the current status of this rapidly evolving field.

1. Introduction

1.1. Anthony Ritaccio

The Second International Workshop on Advances in Electrocorticography (ECoG) was convened in San Diego, CA, USA, on November 11–12, 2010, as a satellite event of the annual meeting of the Society for Neuroscience. Building on the success of the First International Workshop [1], the program was expanded to a 2-day format to adequately represent the explosive growth in knowledge in both clinical and experimental realms. In the year between these gatherings, a much clearer picture has emerged of cortical ECoG physiology and its relationship to local field potentials and single-cell recordings. Similarly, there has been rapid evolution in material engineering of active and passive sensor technology. ECoG continues to evolve as a preeminent direct neural interface in both animal and human brain–computer interfaces (BCIs). Improvements in instrumentation available to the clinical epileptologist, continued elucidation of pathological high-frequency oscillations, and the demonstration of "microseizures" in submillimeter domains redefine the epileptogenic zone and may soon prove transformative in epilepsy surgery planning. Prescient research into the aforementioned developments was at the core of our second gathering. We give our greatest thanks to the authoritative multi-international faculty of ECoG "scale chauvinists," who gave of their time and expertise to present their work as well as contribute to these representative proceedings.

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2. Emerging understanding of electrocorticography physiology: What is inside the electrocorticography signal?

2.1. Kai J. Miller, Josef Parvizi

For many years, observations made with the electroencephalogram (EEG) have made us believe that the brain electrophysiology is about synchronized rhythmic activity of neuronal populations. However, because of the remote distance of the scalp EEG electrode from the cortical surface (~20 mm), the captured electrophysiological signals are necessarily averaged across a large area of the cortical mantle, and therefore any asynchronized pattern of activity within a population of neurons is largely lost to spatial averaging in the scalp EEG measurement.

In contrast to scalp EEG, ECoG offers a closer look into the dynamics of electrophysiological signals within a focal cortical tissue it records from. Given the relative size of ECoG electrodes (~2 mm in diameter), the recording area underneath each electrode resembles the size of a typical voxel in the current neuroimaging methods (i.e., 10 mm^3), which contains ~10–20 functional columns [2] and ~10^5 neurons and 10^9 synapses [3]. Thus, ECoG measures neuronal populations on a much more local scale than recordings from the scalp.

On the basis of earlier work, it is understood that current dipoles between cortical lamina produce macroscale field potentials [4]. Properties of the physiology underlying the current source density (CSD) in different cortical lamina were established experimentally in the late 1970s and early 1980s [5]. We now know that the propagating action potentials in axons and axonal terminals do not contribute strongly to the CSD at spatial scales of ~50–300 μm or greater, for example, the scales where local field potentials (LFP) are pooled from or over which ECoG potentials are averaged. Instead, it is the dendritic synaptic current exchange (i.e., influx and efflux) that modulates the CSD and, by extension, the LFP and the ECoG signal. This has recently been substantiated by simultaneous in vivo recordings of the intracellular potential and the LFP, showing that they are tightly coupled temporally, independent of the spiking pattern of the neuron [6]. As such, one might directly infer properties about the underlying neuronal statistics from the shape of the changes in the electric potential [7,8].

A way to think about the properties of ECoG signals is the degree to which synaptic inputs are in concert and synchronized *across* a population of neurons, compared with the asynchronous pattern of complex local inputs *within* a population of neurons (Fig. 1). Although the EEG is best in capturing fluctuating rhythms, the ECoG trace of asynchronous inputs, when averaged, appears as a type of random walk in time and contains a mixture of various processes such as event-related potentials, rhythmic oscillations, and asynchronous local activity.

In the ECoG, changes in the way local neurons interact with one another will appear as a "speeding up" of the random walk, difficult to see when looking at the raw potential but apparent as broadband, power-law changes when looking in the frequency domain (Fig. 1) [7]. Synchronized changes, by contrast, can be visually apparent in the raw tracing—even if the synchronization is relatively weak, averaging augments the synchronized portion, whereas the other aspects are diminished. If the synchronization is tied to an oscillatory process of some kind (such as the one in the loop between the cortex and subcortical structures), then a "rhythm" will emerge, and the synchronization and desynchronization of the rhythmic process will be revealed as changing amplitude of a sinusoid in the time series and as a peak in the frequency domain. If the synchronization is tied to a feedforward process, such as thalamic input to V1 following a visual stimulus, the time series may reflect a multiphasic, time-locked response, the "event-related potential," where the different portions of the event-locked time series will likely reflect initial input to cortical pyramidal neurons from the thalamus, and then synchronized lateral inhibition. The measured ECoG voltage time series will be then a mixture of random walk-like changes reflecting asynchronous local

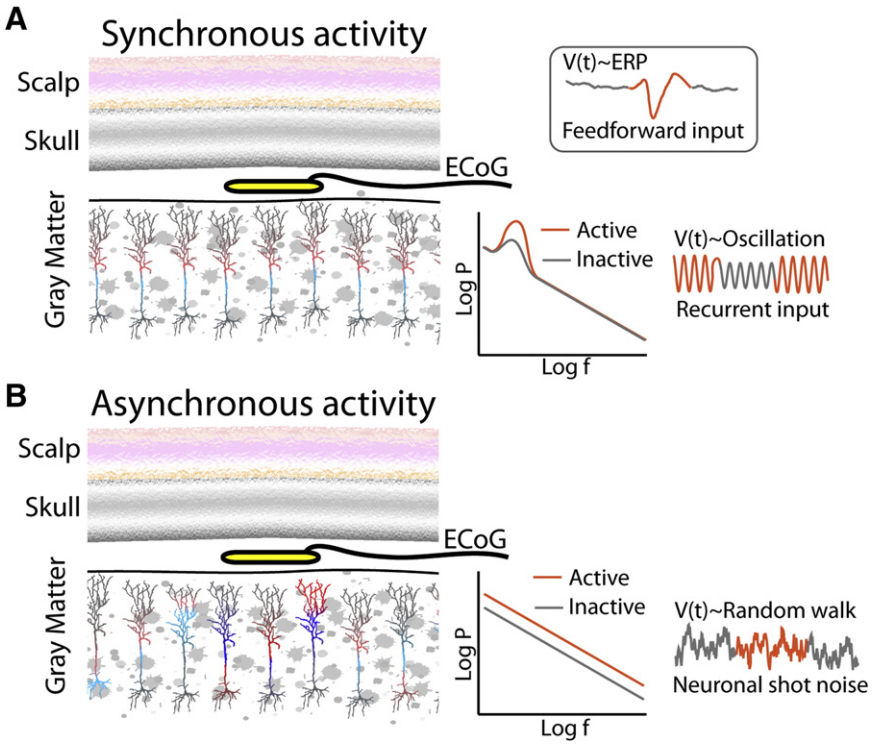

Fig. 1. How synaptic input to a neuronal population might be reflected in the ECoG potential time series $V(t)$. (A) Synchronized activity, feedforward input revealed by transient, multiphasic, event-related potential changes, or recurrent feedback oscillatory inputs revealed by changes in peaked aspects of the power versus frequency spectrum. (B) Asynchronous, local activity revealed by broadband changes in the power versus frequency spectrum. P, power; f, frequency.