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Platinum microwire for subdural electrocorticography over human neocortex: millimeter-scale spatiotemporal dynamics

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***Abstract*—Platinum microwires, terminated at regular intervals to form a grid of contacts, were used to record electric potentials at the surface of the cerebral cortex in human subjects. The microwire grids were manufactured commercially with 75 µm platinum wire and 1 mm grid spacing, and are FDA approved. Because of their small size and spacing, these grids could be used to explore the scale of spatiotemporal dynamics in cortical surface potentials. Electrochemical impedance spectroscopy was used to characterize their recording properties and develop a frequency-dependent electrical model of the micro-electrodes. Data recorded from multiple sites in human cortex were analyzed to explore the relationship between linear correlation and separation distance. A model was developed to explore the impact of cerebrospinal fluid on signal spread among electrodes. Spatial variation in the per-electrode performance decoding articulated speech from face-motor and Wernicke's areas of cortex was explored to understand the scale of information processing at the cortex. We conclude that there are important dynamics at the millimeter scale in human subdural electrocorticography which may be important in maximizing the performance of neural prosthetic applications.**

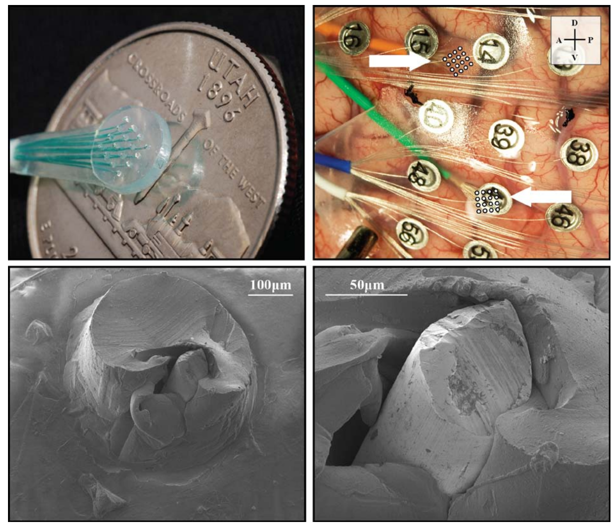

Fig. 1: (Top, Left) Nonpenetrating platinum microwire grid next to a U.S. quarter-dollar. (Top, Right) Microwire grids (indicated by arrows) resting underneath a standard clinical ECoG grid in vivo. (Bottom) SEM images of one micro-electrode at two magnifications.

I. Introduction

BRAIN-computer interfaces (BCIs) using cortical surface potentials must capture the information-bearing spatiotemporal dynamics of the neural activity in order to maximize performance. Standard clinical electrodes for performing electrocorticography (ECoG) are typically several millimeters in diameter and separated by a centimeter. At this scale, each clinical ECoG electrode records from several hundred thousand neurons and may superimpose the activity of multiple functional neuronal assemblies, thereby blurring differential features within channels of recorded data.

Grids of nonpenetrating micro-electrodes (Fig. 1) were designed with significantly smaller electrode size (75 µm diameter) and grid spacing (1 mm) to explore the scale of these dynamics in the context of a BCI application [1-2]. The micro-electrode grids were manufactured commercially and are approved by the FDA for human use (PMT Corporation, Chanhassen, MN).

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II. Methods

A. Electrochemical impedance spectroscopy

A grid of nonpenetrating micro-electrodes was submersed in 0.1M phosphate-buffered saline (PBS) solution, with a saturated calomel electrode (SCE) as reference and a platinum wire as counter electrode. Electrochemical impedance spectroscopy (EIS) was performed using a Gamry Reference 600 Potentiostat to apply small-magnitude AC signals across a range of frequencies and measure the corresponding changes in phase and magnitude.

An electrical model of a single platinum microwire electrode was formulated as a resistive element in parallel with a series combination of a constant phase element (CPE) and Warburg diffusion element (W) (Fig. 2, Table 1). The impedance of the CPE element is a function of radial frequency ω parameterized by $Y_{0,CPE}$, the capacitance, and

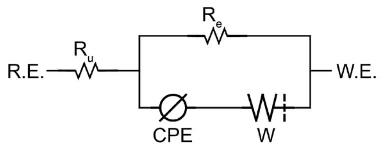

Fig. 2. Electrical model of micro-electrodes used to fit the measured electrochemical impedance spectroscopy data.

TABLE 1. MODEL PARAMETERS FIT TO MEASURED EIS DATA.

	Mean	Std Dev	Units
R_e	53.8	34.1	MΩ
$Y_{0,CPE}$	26.2E-09	16.9E-09	$S*s^{\alpha}$
α_{CPE}	836E-03	35.8E-03	--
$Y_{0,W}$	1.14E-06	1.54E-06	$S*s^{(1/2)}$
β_W	3.60E-03	3.30E-03	$s^{(1/2)}$

α_{CPE}, a non-ideality factor (equal to 1 for an ideal capacitor). The CPE models the electric double-layer at the metal-solution interface. The Warburg diffusion element W models ion diffusion from solution to electrode, and is a function of ω parameterized by an admittance parameter $Y_{0,W}$, and β_W, which accounts for finite thickness of the diffusion layer. Fitted parameters for two of the 16 electrodes were excluded from Table 1 as outliers.

B. SPICE modeling

A resistor mesh (Fig. 3) was designed to model frequency-independent signal propagation through the structure of the cerebral cortex in SPICE [3]. The basic unit of the model represented an area of cortex approximately 0.5 mm^2 in diameter and 4 mm deep, with resistors modeling impedance in three dimensions: two orthogonal dimensions which span the plane of the cortical surface (e.g., **x** and **y** dimensions), and a surface-perpendicular dimension (e.g., **z**). A voltage source was placed between depth layers at 2 and 3 mm to excite the mesh network from within the modeled cortex. Fig. 3 shows a two-dimensional slice (**x** and **z** dimensions) of the model. Sufficient replicas of the basic three-dimensional unit were arranged to model a volume of cerebral cortex large enough to provide coverage for a full 16-channel micro-electrode grid.

Within the cerebral cortex portion of the model, resistivity parallel to the cortical surface was set at 6 Ω/m, and resistivity perpendicular to the cortical surface was set at 5 Ω/m. The slight offset in these impedances was intended to model local neuronal assemblies working synchronously to process similar types of input stimuli. The resistivity perpendicular to the surface corresponds to the reported conductivity of gray matter, 0.2 S/m [4].

A second resistor mesh was added to the "surface" of the modeled cerebral cortex to represent cerebrospinal fluid (CSF). An electrical model of the micro-electrodes, with parameters fitted from the measured EIS data, was connected to the CSF layer. A very high impedance represented the amplifier input. The resistivity of the CSF resistor mesh was swept between 0.2 Ω/m and 2 kΩ/m. A resistivity of 0.56 Ω/m corresponds to the reported conductivity of CSF, approximately 1.8 S/m [5].

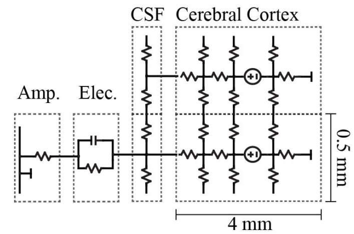

Fig. 3. Resistor mesh modeling amplifier input, electrode, CSF, and cortex, for 1 mm of cortical surface (in a single dimension) and 4 mm of depth.

The resistor mesh model was excited with uncorrelated pink noise generated within each modular unit. The pink noise was created by filtering white noise to mimic the 1/f power-law characteristic of cortical field potentials, then bandpass filtering to retain frequencies between 30 Hz and 200 Hz. These inputs were fed into the resistor network using piece-wise linear voltage sources. While simulating the full circuit in SPICE, voltages were probed at the amplifier input. Correlation coefficients were calculated for this simulated data in a similar fashion as was used for the measured data.

C. Data collection

In a study approved by the Institutional Review Board, and with the informed consent of the subject, data were recorded from micro-electrode grids resting subdurally on the cerebral cortex. Data were referenced to the clinical reference lead and were amplified, bandpass filtered with cutoff frequencies at 0.3 Hz and 7500 Hz, and digitized at 30,000 samples per second (Neuroport system, Blackrock Microsystems, Salt Lake City, UT).

Data recorded from one patient were used in this study. Micro-electrode grids rested over face-motor cortex (FMC) and Wernicke's area, and the patient repeated words into a microphone while neural data and audio data were recorded.

D. Signal processing

Prior to calculating correlation coefficients, raw data were filtered using an IIR notch filter to attenuate noise at 60 Hz and harmonics. Bandpass filtering was performed as needed using a 13^{th}-order elliptical filter with 0.1 dB of passband ripple and 60 dB of stopband attenuation. Data were not common-average re-referenced.

Correlation coefficients were calculated in five-second windows, with a step size of one second. Coefficients calculated for moving windows over 120 seconds of data, primarily during attended task, were averaged to form an estimate of the correlation between each pair of channels. Time-averaged coefficients for all sets of channels separated by a common distance were further averaged to form an estimate of correlation as a function of separation distance.

Trial-averaged multi-tapered spectrograms were generated using 250 ms windows, 50 ms step size, a time-bandwidth product of 5, and 9 leading tapers (Chronux, [6-7]). Data were re-referenced to the common average of channels in the

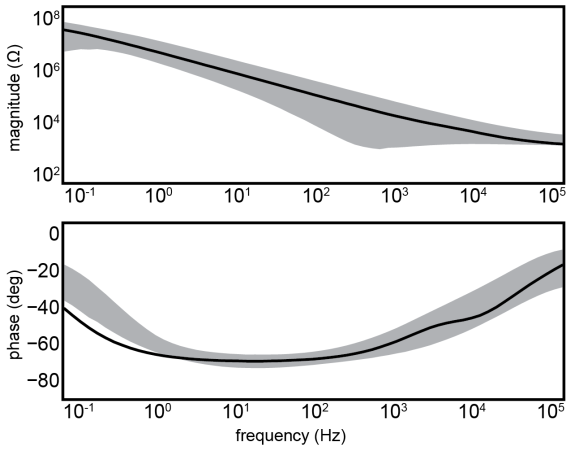

Fig. 4. Measured impedance magnitude and phase (shaded areas indicating standard deviation) with the response of the fitted model overlaid (thick black trace)

same grid prior to estimating the frequency content. Spectrograms were log-normalized across time to emphasize temporal dynamics over the frequency-domain power-law trend [8].

Data processing, feature selection, and classification methods for the speech classification were described in [1].

III. RESULTS

A. Recording characteristics

The micro-electrodes demonstrated log-linear impedance magnitude, dropping from several MΩs at very low frequencies to several kΩs at very high frequencies. At 100 Hz, well within the range of frequencies important to BCI applications, the magnitude was 297.3 ± 283.1 kΩ (mean ± s.d.). In the range between 1 Hz and several hundred Hz the phase of impedance was relatively stationary around -72.5 degrees (Fig. 4). The mean goodness-of-fit across all model parameters and all1 6 electrodes was 3.76×10^{-3}.

B. Correlations in measured data

Correlation as a function of distance in measured data showed strong linear relationships at the millimeter scale which decreased with increasing distance (Fig. 5). Unfiltered data were highly correlated with coefficients of 0.92 (FMC) and 0.96 (Wernicke's area) at 1 mm spacing, and 0.78 (FMC) and 0.80 (Wernicke's area) at 4 mm spacing. Data filtered to include only activity in the gamma (30-80 Hz) and high gamma (80-200 Hz) frequency bands had correlation coefficients of 0.79 (FMC) and 0.77 (Wernicke's) at 1 mm spacing and 0.37 (FMC) and 0.27 (Wernicke's) at 4 mm spacing.

C. Modeling the impact of CSF on channel correlation

The resistor mesh modeling tissue and electrodes was simulated in SPICE, and correlations in the voltage probed at the electrode-amplifier interface were calculated for several separation distances as a function of CSF conductivity (Fig. 6). With very low conductivity in the CSF layer, simulations

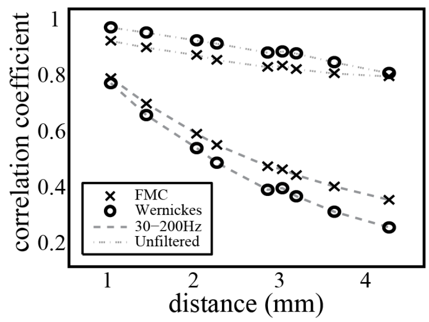

Fig. 5. Correlation vs. distance for data recorded *in vivo*.

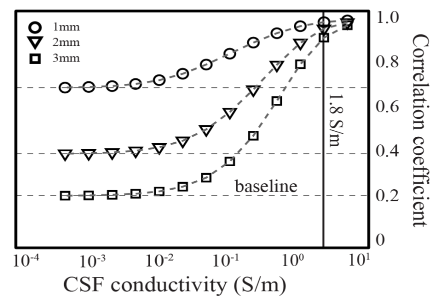

Fig. 6. Correlation coefficients calculated for simulated data from neighboring microwires as the conductivity of the CSF element in the SPICE model varied.

predicted a baseline correlation at the cortical surface, due to spread through the cerebral cortex resistor network, of ρ = 0.70 for 1 mm spacing, which is close to the measured values of 0.79 and 0.77 for FMC and Wernicke's area, respectively.

Introducing a layer of increasing conductivity (which could correspond, for example, to increasing thickness in the CSF layer) at the tissue-electrode interface strengthened linear relationships. At the reported conductivity of CSF, electrodes 3mm apart were 92% correlated. Comparing *in vivo* measurements to these simulated results suggests a conductivity of between 0.05 S/m and 0.25 S/m at the cortical surface.

D. BCI performance

Informal observation of trial-averaged spectrograms showed dynamics in space, time, and frequency that appeared to vary with the word spoken (Fig. 7 and 8). With spectrograms normalized across time, modulation in spectral power appeared to be time locked to the articulation of speech across a broad range of frequencies. The specific pattern of modulation varied across channels with significant changes in patterns of frequency, time, or both dimensions occurring at separations of one or several millimeters. Generally, data recorded over FMC showed more task-related change in spectral power than data recorded over Wernicke's area. The samples shown in Fig. 7 and Fig. 8, for articulations of the words "thirsty" and "hello", are representative of trial-averaged spectrograms for other words.

Speech was classified from these same cortical surface potentials recorded over FMC and Wernicke's area [1]. In

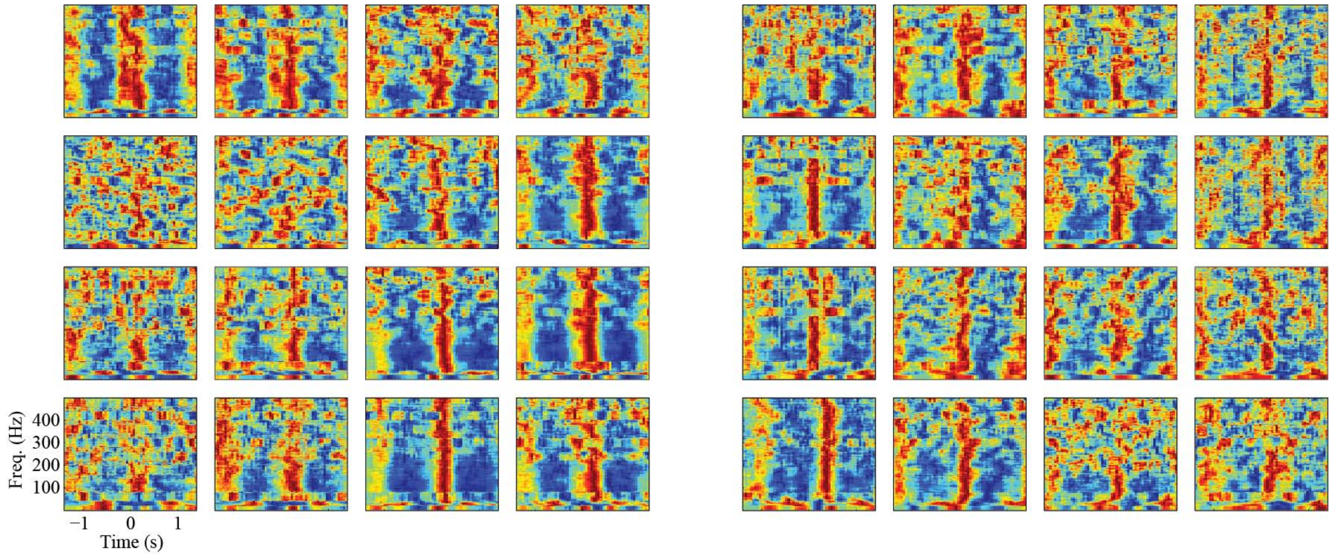

Fig. 7. Trial averaged spectrograms for 16 channels of data recorded over FMC (left) and 16 channels of data recorded over Wernicke's area (right) while the subject repeated the word "thirsty". Each set of 16 channels is arranged in the original grid layout. The color scale represents normalized spectral power.

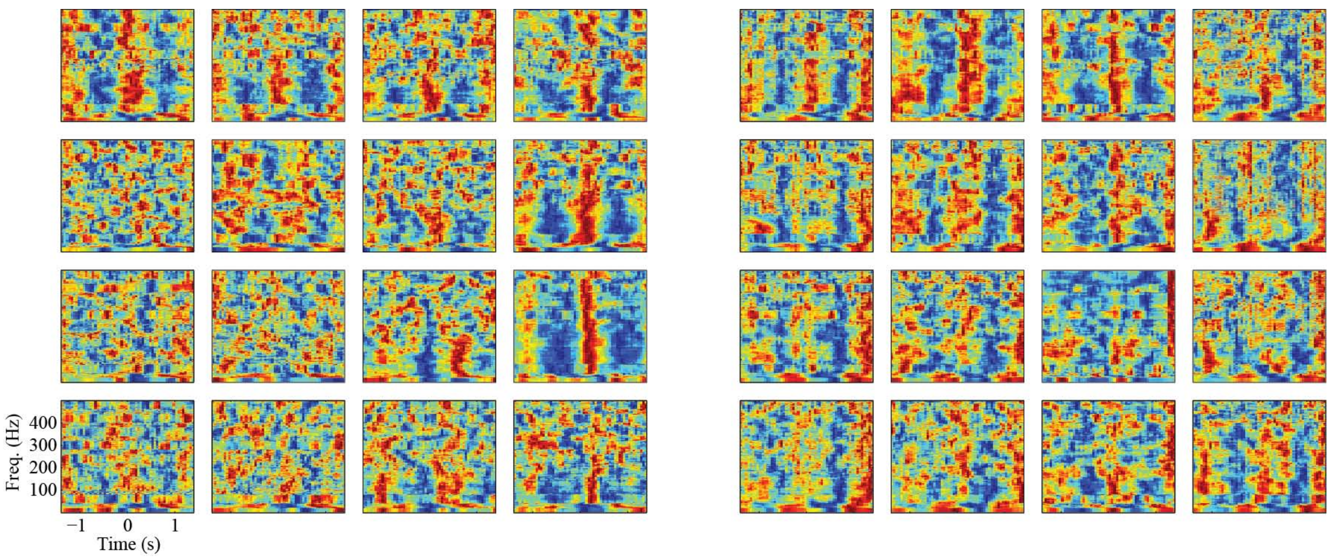

Fig. 8. Trial averaged spectrograms for 16 channels of data recorded over FMC (left) and 16 channels of data recorded over Wernicke's area (right) while the subject repeated the word "hello". Each set of 16 channels is arranged in the original grid layout. The color scale represents normalized spectral power.

that study, twenty-nine of 32 microwires had a neighbor within 1.4 mm (including diagonals) whose most accurately classified word was different, while 13 of 32 microwires classified their most accurate word at least 15 percentage points better than a neighbor. These performance deltas occurred in multiple channels of data recorded within the area of a single macro electrode.

IV. Discussion

A. Micro-electrodes record surface local field potentials

Results from human subdural electrocorticography, from simulated models of the cerebral cortex, and from a speech-prosthetic BCI application have all demonstrated millimeter-scale dynamics in neural activity recorded from the cortical surface. In each case, data were either measured or simulated using platinum microwires (or an equivalent electrical model). Because of their recording characteristics and grid size and spacing, these electrodes appear to be well suited to capturing the information-bearing dynamics of the activity of the brain insofar as these dynamics are available at the cortical surface.

Because of their small size, these nonpenetrating micro-electrodes are likely to record activity local to the electrode tip. Relatively flat phase across the important range of frequencies below several hundred Hz indicates that frequency-dependent distortion is unlikely to impact analysis results or BCI performance. Because the impedance magnitude is orders of magnitude lower than the amplifier impedance, the impedance itself is unlikely to affect the recording characteristics. However, impedance may be a useful proxy representing other influential characteristics of the recording electrode, such as exposed surface area.

These recording characteristics suggest that the signal recorded by nonpenetrating micro-electrodes could be different than the signal recorded by clinical ECoG electrodes. Because clinical electrodes are larger in diameter and have lower impedance, they sense activity from larger regions of cortex. The activity recorded by microwires, from a more local region of cortex, could be termed a "local surface potential," or LSP.

B. Reducing signal spread through CSF

Signal spread through tissue and fluids could reduce the spatiotemporal resolution of the signal dynamics. Identifying and mitigating avoidable causes of signal spread could yield more information in the recorded activity. CSF has a reported conductivity of 1.8 S/m—9 times more conductive than gray matter [4-5]—and could allow significant signal spreading between closely spaced electrodes, depending upon the thickness of the CSF layer and electrode-contact profiles. The grid design used in this study featured a silicone protrusion at each electrode site meant to help the grid adhere to the cortical surface, with the additional benefit of shielding the electrodes from CSF. Despite imperfections in the commercial manufacturing process (Fig. 1), such a design feature may actually help to improve the performance of micro-electrodes by reducing the amount of signal spread through CSF at the cortical surface.

C. Room for improvement in the SPICE model

The SPICE resistor mesh simulations do not perfectly represent the significant complexities of the human neocortex. For example, electrical sources were represented as discrete voltage sources within each organizational unit, missing both the complexities of ion flow driven by populations of neuron firings and synaptic activity, as well as inputs from other cortical areas. The resistor mesh, while modeling potential differences in lateral vs. vertical dimensions, was otherwise evenly and symmetrically organized, unlike the tortuous mesh of tissue in the cortex. Furthermore, some correlation in neural activity is likely to be inherent in the synchrony among functional areas necessary to produce coherent physical outputs.

The impedance of gray matter has been shown to be isotropic in surface-parallel planes and across cortical layers [3]. Although the model used in this study did separate the cortex into layers of resistors, these were not intended to accurately capture the properties of the different anatomically defined cortical layers. Rather, surface-parallel resistivity was set slightly higher than surface-perpendicular resistivity to approximate the synchronous activity of populations of neurons, perhaps loosely organized in surface-perpendicular oriented assemblies, working to process similar kinds of stimuli, e.g., cortical columns and related findings [9-10].

Despite limitations, a resistor mesh may be a reasonable approximation of cortical tissue since previously measured impedances of cortical tissue have shown no dependence on frequency [3]. The SPICE model estimates, to a first order, propagation in the cortex and potential signal spread through CSF at the cortical surface. Because the performance of an ECoG BCI is so tightly coupled to the accurate measurement of information-bearing dynamics, the indicated potential for blurring of features could be detrimental. Electrodes intended for ECoG BCIs should be designed to minimize signal spread through CSF in order to maximize information recorded from the neural activity at the cortical surface.

V. Conclusion

Electrochemical measurements and data analyses have demonstrated the utility of commercially manufactured, FDA-approved platinum microwire grids for neural recording. Linear correlations, decreasing with separation distance were found to exist in data recorded at millimeter spacing. Variance in the dynamics of neural activity was also found at the millimeter scale in cortical activity recorded during speech articulation. Simulation of a conductive layer at the cortical surface has illustrated the potential consequences of conductive pathways through CSF between electrodes. These results motivate continued investigation of electrode design for neural prostheses using ECoG, and illustrate the impact of accurately capturing millimeter-scale dynamics of cortical surface potentials on BCI performance.

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