31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Evaluation of Micro-Electrocorticographic Electrodes for Electrostimulation

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***Abstract*—Chronic neural recording and stimulation on the surface of the cortex with macroelectrodes has been shown to be promising for treating a wide range of neurological deficits. To enhance the specificity of these devices, dense arrangements of small area electrodes have been microfabricated for precise recording and control of neural populations. In this study micro-electrocorticographic (μECoG) electrodes were evaluated for electrostimulation. Surface modification with electrodeposited iridium oxide (EIrOx) resulted in lower impedance, higher charge carrying capacity, and lower, more linear voltage excursions during current controlled stimulation.**

I. Introduction

NEUROPROSTHETIC brain-computer interface (BCI) systems have received interest in the neuroengineering field for treatment of some neurological injuries and disorders. Electrocorticogram (ECoG) recordings taken from electrodes on the surface of the cortex have been successfully implemented for BCI control [1-3] and more recently μECoG devices have been fabricated with a dense arrangement of small-area microelectrodes on the order of 100s of microns for increased spatial resolution [4]. While these devices are commonly studied for output-type neural prosthetic systems, input-type systems may also be applicable to treat neurological problems including sensory deficits, Parkinson's disease, epilepsy, and depression.

Electrical stimulation on the surface of the primary sensory regions of the cortex has long been shown to evoke sensation [5, 6]. A group of patients who received the first cortical prostheses stimulating the surface of the primary visual cortex displayed sensory thresholds typically between 1-5 mA, which was not dependent on electrode size [7]. With the goal to decrease stimulation thresholds and increase spatial resolution, smaller, penetrating electrodes also have been used successfully in delivering behaviorally relevant information [8-11]. The major disadvantage of penetrating the cortical surface is the tissue response associated with insertion and the chronic presence of the device [12, 13].

The main problems with using μECoG devices for electrostimulation result from delivering current on the order of a few microamps through high impedance sites with diameters on the order of 100s of microns. Delivering such charge densities requires relatively high voltages which can result in toxic redox reactions detrimental to both the electrode and tissue. Improvements in charge transfer have been shown through the application of different surface modifying materials such as iridium oxide [14], poly(3,4-ethylene dioxythiophene) or PEDOT [15, 16], and carbon nanotubes (CNTs) [17].

This report evaluates flexible polyimide μECoG devices for electrostimulation. Bare platinum electrodes and platinum electrodes modified with electrodeposited iridium oxide were characterized through electrochemical impedance spectroscopy (EIS), cyclic voltammetry (CV), and voltage excursion measurements in saline

II. Materials and Methods

A. μECoG Electrode Arrays

Fabrication of μECoG electrode arrays has been described in detail elsewhere [4]. In brief, electrode sites made with

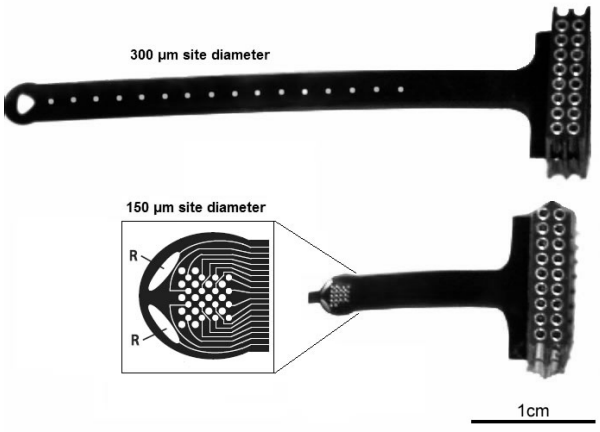

Fig. 1. μECoG electrode arrays. The 1x16 array on top contains large site sizes (300 μm diameter). The 4x4 array on bottom is better equipped for *in vivo* applications with small site sizes (150 μm diameter), two large area reference (R) sites, and holes to promote consistent perfusion.

Manuscript received April 23, 2009. This work was supported in part by the Purdue Research Foundation.

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200 nm of gold and 10 nm of platinum on top were plated onto a flexible polyimide platform. μECoG electrodes used in this study include a 1x16 array of 300 μm diameter sites spaced 1.5 mm apart and a 4x4 array of 150 μm diameter sites spaced 400 μm apart as seen in fig. 1. The 4x4 array equipped with holes to promote consistent perfusion and two large area reference electrodes is well suited for implantation over the rat cortex.

B. Electrochemical Characterization

Electrochemical measurements were made using an Autolab Potentiostat/Galvonostat PG-STAT12 (Eco Chemie, Utrecht, Netherlands) with a built-in frequency response analyzer (Brinkmann, Westbury, NY). A three-electrode cell configuration in 1X phosphate buffered saline (PBS) was used. The microelectrode site, a large-area platinum wire, and an Accumet, gel-filled, KCl saturated calomel electrode (Thermo Fischer Scientific, Fair Lawn, NJ) functioned as the working electrode (WE), counter electrode (CE), and reference electrode.

EIS measurements were collected by configuring the Autolab to sequentially inject overpotentials of 5 mV_{RMS} sine waves at 36 frequencies logarithmically spaced from 1 Hz to 1 MHz. CV measurements were collected by configuring the Autolab to sweep the voltage of the WE between +0.8 V and -0.6 V at 50 mV/s and monitor the resulting current flow between the WE and CE. The cathodal charge storage capacity (Q_{cap}) was calculated by integrating the cathodal current density enclosed by the CV and dividing by the sweep rate.

Voltage excursion measurements were collected during the delivery of constant current pulses in 1X PBS. Cathodal-first, charge-balanced, biphasic current pulses were applied between the microelectrode site and a large-area platinum wire. 500 μs phase durations and 100 μA – 1 mA current amplitudes were applied at a pulsing frequency of 50 Hz. The voltage excursions were measured with respect to the platinum wire.

C. Electrodeposited iridium oxide (EIrOx)

Iridium oxide was electrodeposited in a solution of 4 mM $IrCl_4$, 40 mM oxalic acid, and 340 mM K_2CO_3 using a previously documented protocol [14]. In brief, the potential was first cycled 50 times between 0.0 V and 0.55 V at a sweep rate of 50 mV/s followed by cathodic and anodic biasing at the same potential limits for 1600 seconds at a pulsing frequency of 1 Hz.

III. Results and Discussion

A. Electrochemical Characterization

EIS data were collected in PBS between 1Hz and 1 MHz for the two μECoG electrode sizes. Fig. 2a shows the impedance magnitude values were lower for the larger electrode sizes across all frequencies. The 1 kHz impedance magnitudes are of particular interest since the fundamental frequency of an action potential is approximately 1 kHz. The 150 μm diameter electrodes displayed a 1 kHz impedance magnitude of approximately 100 kΩ which was about one order of magnitude greater than that of sites double in diameter.

CV measurements were collected to evaluate the presence of electrochemical reactions, the double-layer capacitance, and the charge available at the interface (Q_{cap}). A slow sweep rate (50 mV/s) was used to assess the near equilibrium voltage/current relationships. As seen in fig. 2b, the bare platinum interface displays relatively smooth CVs and low Q_{cap} values less than 1 mC/cm^2. For stimulation applications only a small percentage of the equilibrium Q_{cap} can be accessed during fast current pulsing. For this reason, bare platinum is not suitable for safely delivering current on the order of milliamps, and surface modification is often necessary to increase the electrochemical surface area and improve the charge transfer properties of the electrode-electrolyte interface.

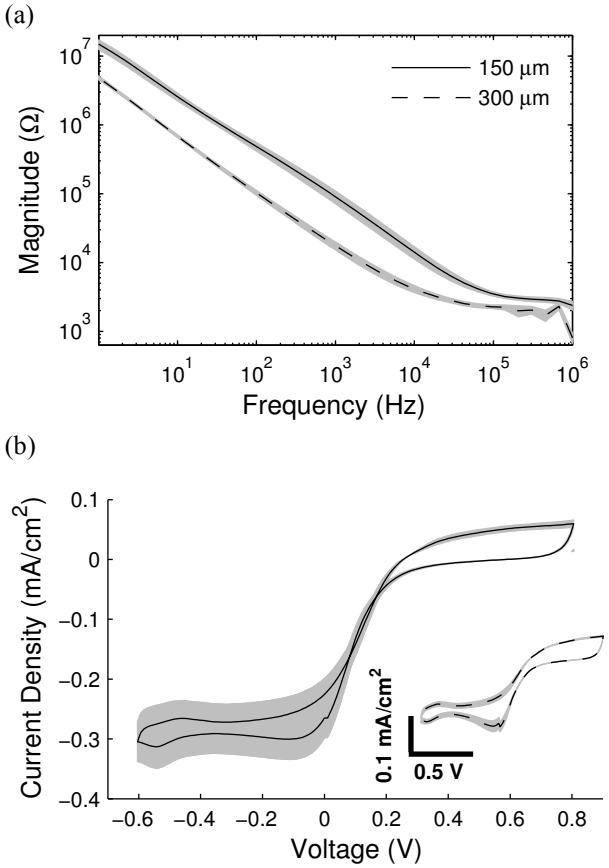

Fig. 2. Electrochemical characterization; (a) mean impedance magnitude for 36 frequencies logarithmically spaced between 1 Hz and 1 MHz, (b) mean CVs taken between -0.6 V and +0.8 V with a sweep rate of 50 mV/s for 150 μm diameter sites (insert: 300 μm diameter sites). The grey areas represent standard error.

B. Electrodeposited iridium oxide (EIrOx)

Iridium oxide has commonly been used to modify the surface of microelectrodes for electrostimulation and can easily be activated on iridium electrodes or electrodeposited

on other metal surfaces [14]. EIrOx increases the electrochemical surface area of the electrode and improves charge transfer through electron exchange that occurs during reversible oxidation and reduction reactions.

As expected, application of EIrOx to the µECoG electrode sites significantly improved the interface for charge transfer represented by the larger CV shown in fig. 3a. The EIrOx modified sites displayed characteristic peaks associated with the reversible oxidation and reduction of iridium. EIrOx greatly increased the charge available at the interface corresponding to an increase in Q_{cap} to 34.2 mC/cm^2 for the 150 µm diameter sites and to 14.8 mC/cm^2 for the 300 µm diameter sites (fig. 3b). The same iridium oxide deposition duration was applied for both electrode sizes which explains why the smaller electrodes displayed a larger Q_{cap}. Interestingly, the 1 kHz impedance magnitude dropped to similar values for the two site sizes: 2.7 kΩ for the 300 µm electrode sites and 3.0 kΩ for the 150 µm electrode sites (fig. 3c).

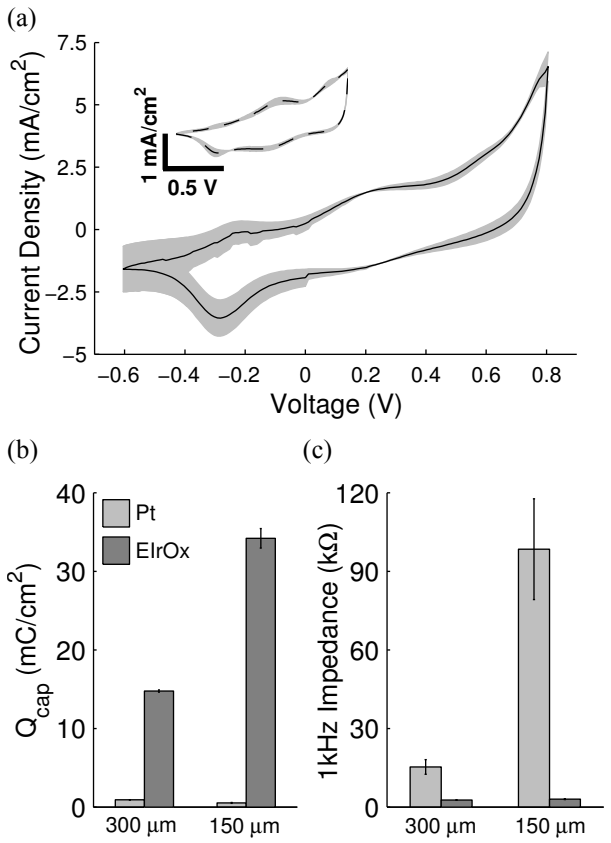

Fig. 3. EIrOx modification; (a) 150 µm diameter sites coated with EIrOx showed an increased CV curve with peaks characteristic of iridium oxide (insert: 300 µm diameter sites). This resulted in increased (b) Q_{cap} and decreased (c) 1 kHz impedance magnitude. Grey regions and error bars represent standard error.

Monitoring the amplitude and shape of the resultant voltage excursions during current controlled stimulation is often done to evaluate the safety of the interface during charge transfer. A common limitation is operating within the potentials which result in hydrolysis. Limits commonly used for platinum and iridium oxide electrodes are +0.8 V and -0.6 V. Exceeding these limits could result in trauma due to changes in pH as hydrogen and hydroxide ions build up.

300 µm diameter sites were pulsed at biologically relevant parameters at an amplitude of 1 mA and a phase duration of 500 µs before and after application of EIrOx. EIrOx modified sites displayed a lower amplitude voltage excursion as seen in Fig. 4a. Further, the EIrOx voltage excursion exhibited a much more ohmic representation of the applied current pulse.

Because of the voltage compliance of the stimulator device, the current amplitude was reduced to 100 µA for the 150 µm diameter sites as seen in fig. 4b. Similar to that seen with the larger electrodes, the EIrOx modified surface displayed a more linear, low amplitude voltage excursion. Prior to EIrOx modification the platinum voltage excursions exceeded the limits of hydrolysis during 100 µA pulsing. The EIrOx modified electrode operated within +/- 0.2 V, well within the limits of hydrolysis. Additionally, the stimulator was able to operate within its compliance voltage during application of 1 mA current pulses.

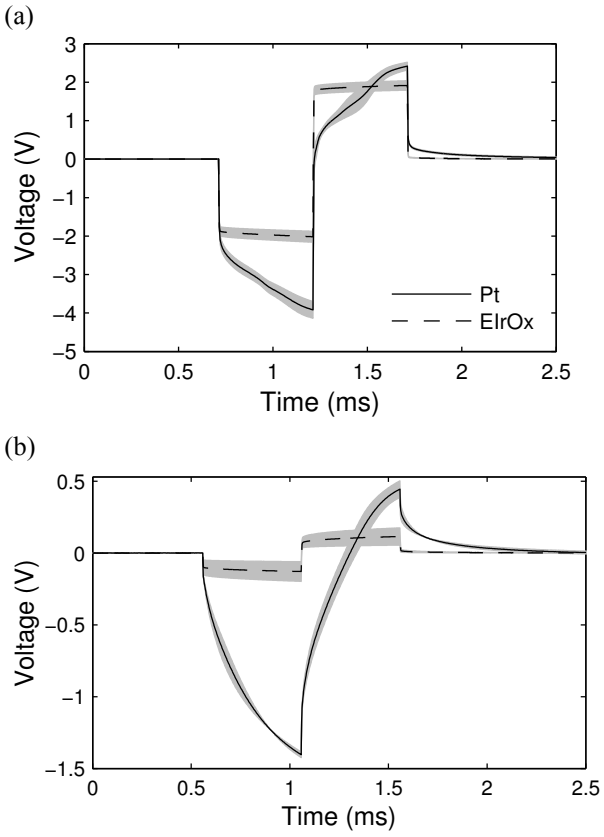

Fig. 4. Voltage excursions; (a) 1 mA current pulses were delivered through the 300 µm diameter sites and (b) 100 µA current pulses were delivered through the 150 µm diameter sites. EIrOx decreased the voltage excursion amplitude and displayed a more ohmic representation of the current pulse. Grey areas represent standard error.

µECoG systems present a unique neuroprosthetic platform between devices placed outside the skull and those penetrating the brain. They can provide more selective

stimulation than transcranial stimulation and reduce short- and long-term complications with electrode placement and presence because they are less invasive than penetrating arrays. The main concern with cortical surface stimulation with electrodes on the order of 100s of microns in diameter is the ability to operate at large charge densities without causing tissue trauma. While iridium oxide greatly improves charge transfer properties, its long-term stability may be a problem. Delivering current pulses at an amplitude of 1 mA and phase duration of 500 µs with 150 µm diameter electrodes results in a charge density of approximately 3 mC/cm^2. Application of such charge densities has been shown to cause iridium oxide instability resulting in damage to both the electrode and tissue [18, 19].

Further exploration into long-term electrochemical stability and efficacy in neural activation must still be done. Additionally, because of the relatively large amplitudes required for cortical surface stimulation, alternative coatings with better charge transfer properties than iridium oxide must be developed. Materials such as PEDOT and CNTs have recently emerged as potential materials for neural stimulation and have successfully been applied to electrode surfaces [15-17]. PEDOT coatings have been reported as having a Q_{cap} as much as three times greater than that seen with iridium oxide [20] and CNTs have become very popular in the miniaturization of electrical devices. Additionally, these materials are attractive for biological applications because they can be functionalized with bioactive molecules. Further work on improving the stability of these coating must be done to validate their chronic application.

IV. Conclusion

µECoG platinum electrode arrays were evaluated for electrostimulation. EIrOx modified electrodes displayed a low impedance magnitude and a high Q_{cap}. During constant current stimulation, EIrOx modified electrodes exhibited low amplitude and linear voltage excursions. The data presented in this report suggest surface modified µECoG electrodes are practical for electrostimulation applications.

Acknowledgment

The authors would like to thank the Purdue NeuroProstheses Research lab for helping in the preparation of this manuscript.

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