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# Identification and Quantification of Electrical Leakage Pathways in Floating Microelectrode Arrays*

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*Abstract*— **The long-term reliability of neural recording and stimulation electrode arrays is becoming the limiting factor for neural interfaces. For effective electrode design, electrical connection to the surrounding neural tissue and fluid should be limited to the electrode tips, with all other leakage currents minimized. It is the goal of this study to identify and quantify electrical leakage within commercially available floating microelectrode arrays (FMAs). Both short term and accelerated stress tests were performed on entire FMAs, as well as on individual electrodes typical of such arrays. Preliminary results of these tests indicate that leakage currents are present due to water penetration of their insulation layer initially, but that prolonged water exposure at high temperature may seal the defects that cause these currents. SEM photos taken of the electrode shafts show extensive defect regions that may correlate with the test data.**

## I. Introduction

The long-term reliability of neural recording and stimulation electrode arrays is rapidly becoming recognized as a limiting factor for *in-vivo* neural interface developments that are being pursued for brain machine interfaces, stimulation of paralyzed muscle, and neural control of artificial limbs. Shaft microelectrodes consist of an insulated shaft conductor that is de-insulated at the tip. In principle, only the exposed tip should have electrical connection to the surrounding tissue and fluid. An electrode array consists of a group of shaft microelectrodes held within the array superstructure. Within the superstructure connecting leads, or possibly active electronics connect to the electrodes. In a simplistic model, no "leakage current" flows through the shaft insulation, or within the superstructure, either to the surrounding fluid or between the array electrodes.

In reality, the system is more complex than the model, and leakage currents can be found in a variety of places, including the electrode shaft, the wire connector, and between multiple electrodes in an array. Good electrode and array design practices attempt to minimize all leakage currents so as to maximize the effectiveness of the electrode array as a transducer of neural signals.

Some of the causes of leakage currents are expected; for example, capacitive coupling between the electrode shafts through the shaft insulation causes measureable AC leakage currents that increase at higher frequencies. This phenomenon is a function of the nature and thickness of the insulation and cannot be eliminated. Other leakage sources are less obvious and more elusive; for example water permeation within the shaft insulation may cause leakages to increase above that predicted by capacitive effects alone. Microscopic defects in the shaft insulation can effectively create many small leakage pathways that can summate to cause significant leakage current, even though they each have an extremely high resistance when considered in isolation. Packaging defects can cause leakages to occur within the superstructure, along a connecting cable, or at the site of a percutaneous connector. All of these can confound neural interface experimentation and clinical deployment, particularly when the leakages increase following implantation.

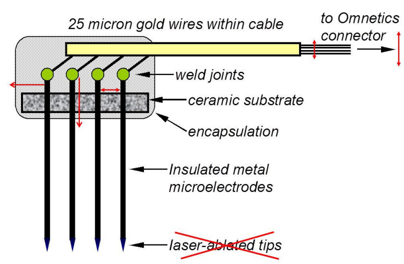


Figure 1. Diagram of possible leakage pathways in an FMA indicated by arrows.

It is the goal of this study to identify and quantify electrical leakage within neural stimulation and recording microelectronic arrays available from Microprobes for Life Sciences (MLS).

## II. Materials and Methods

### A. Electrodes and Electrode Arrays

Floating microelectrode arrays (FMA) and single insulated shaft electrodes were obtained from MLS. The electrode arrays were manufactured identically to commercially available FMAs with the exception that the electrode tips were not exposed (Figure 1). By keeping the electrode tips insulated, we eliminated the normal current pathway from each electrode to the surrounding fluid, and thus ensured that any currents seen during our testing would be unexpected and categorized as leakage, thus dramatically raising the sensitivity of measurement above that which would be normally achievable using de-insulated electrode tips.

This method was designed to maximize our ability to investigate the cause of undesirable leakage currents within the FMAs. The single electrodes used were the same type used in the commercially available arrays, but again were not

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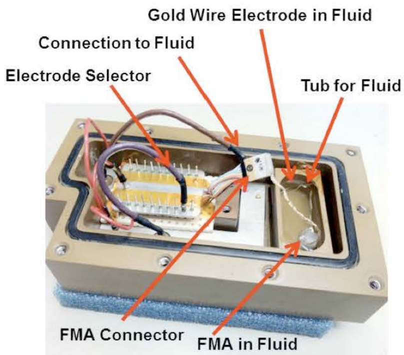


Figure 2. Photograph of the experimental fixture for leakage measurements.

de-insulated; these were used to investigate the leakage characteristics of electrodes independent of the array superstructure.

### *B. Instrumentation*

A Schlumberger Solartron 1260 Impedance/Gain-Phase Analyzer, a Keithley 428 Current Amplifier, and a Keithley 705 scanner were used to make impedance measurements. These instruments were controlled by and returned data to a LabVIEW program that plotted and stored data for viewing and future analysis.

### *C. Experimental Methods*

To test for leakage current between the electrodes and the surrounding fluid, we designed a low-leakage fixture that would place an electrode array and a single gold wire in a fluid bath of phosphate-buffered saline (PBS), as shown in Figure 2. All electrical connections and wires were shielded to restrict leakage current to the array itself.

Before each series of measurements, a background measurement was taken with the electrode unplugged and no fluid present in the setup. This gave a baseline which represented the measuring limitations in the test fixture. Each measurement took three to four minutes to accurately measure response at low frequencies (0.1 Hz).

Next, the selected electrode was connected by manually moving the shielded wire on the Electrode Selector, and a measurement was made with no fluid present. This dry measurement showed the ideal performance of the electrode and array, and is the measurement against which subsequent wet measurements were compared.

Finally, the fluid bath was filled and wet measurements were taken at various time intervals after electrode submersion. Both short-term (<3 hour) and long-term (>1 day) tests were performed to show both the immediate and long-term effects of saline exposure on leakages. For some arrays, short-term tests were followed by long-term tests after the first day.

An accelerated degradation test was performed on one electrode array (A4) using a similar procedure as the standard long-term test with the solution heated to 70ºC.

To examine the effects of saline submersion upon an individual microelectrode independent of the array structure, three single electrodes (P2, P4, and P8) were obtained and tested with the tip placed within the fixture's fluid.

A scanning electron microscope was used to observe the surface of the electrode shafts and view any potential defects in the parylene C insulating layer.

## III. Results

### *A. Short-term wet tests*

We expected that the capacitance value of each electrode would increase in the presence of PBS due to water having a higher dielectric constant than air. A drop in impedance value at a constant frequency would show this effect. Leakage current, if present, was expected to initially cause a downward trend in the asymptotic low-frequency impedance (real component).

Short-term wet tests were performed on arrays A2, A3, and A4 using electrode (pin) 17 on each array. Impedance Scans were run on each electrode immediately (<5 min), and at several intervals after submersion. All three were left

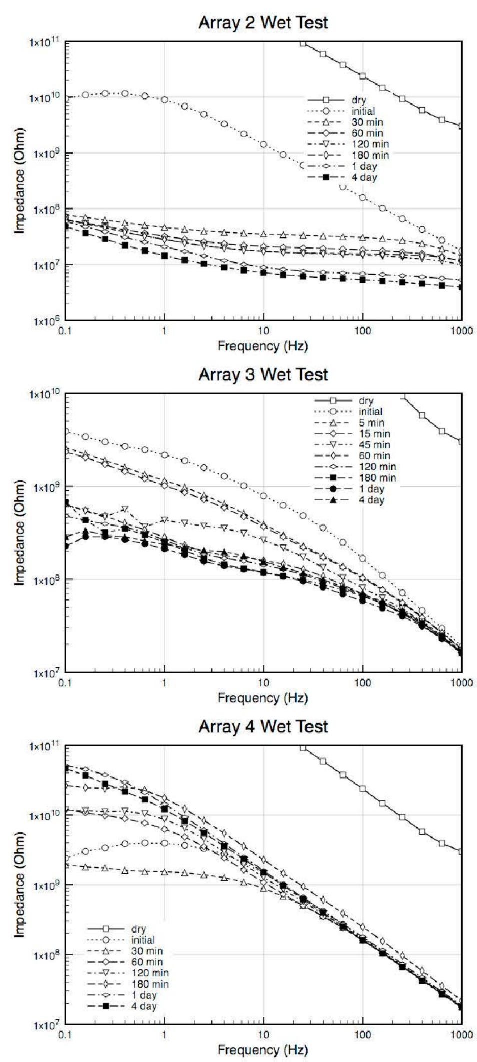


Figure 3. Wet test results for pin 17 of arrays 2, 3, and 4.

submersed and scanned after one and four days to observe longer-term effects of fluid submersion. All three showed both a drop in impedance and a pronounced leakage current curve immediately after submersion in PBS, but their responses differed over time (Figure 3).

The shape of A2's low-frequency impedance curve became resistive after 30 minutes, with the magnitude of the low-frequency resistance decreasing over a 4-day period of time.

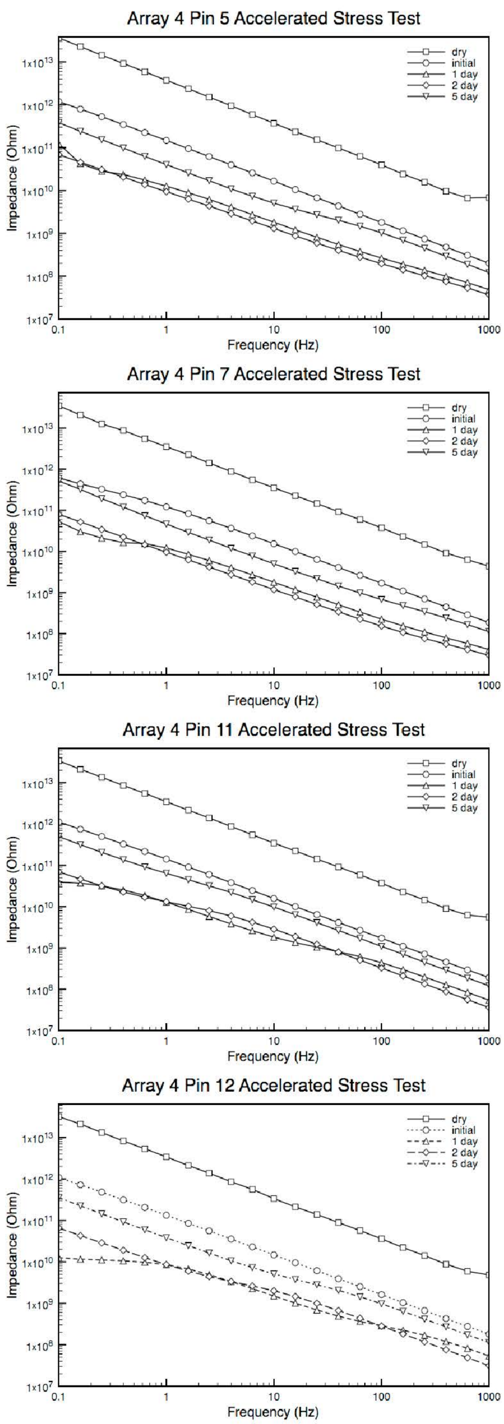


Figure 4. Accelerated stress test results for pins 5, 7, 11, and 12 of array 4.

The normal high-frequency capacitance was seen for both A3 and A4, but the low-frequency resistive leakage current curve became gradually more pronounced, with time, in A3, while the opposite was seen in A4 – for A4 some sort of recovery phenomena was observed. These trends continued through the initial 180-minute test and in both the one- and four-day scans.

### *B. Accelerated degradation tests*

For this test, the same setup was used as in the short-term wet tests, but four electrodes (pins 5, 7, 11, and 12) on array (A4) were chosen. First, a dry measurement was taken of each electrode. The array was then submersed into room temperature PBS and an immediate (<5 min) scan was taken. The array was then placed into the 70ºC PBS with the connector end of the array held in desiccant to restrict water degradation to only the electrode array. Scans of each of the four electrodes were taken after one, two, and five days to observe the long-term effects of water exposure on electrode performance.

As shown in Figure 4, all four electrodes showed an expected drop in impedance due to the dielectric constant of water when initially submersed. Pin 7 also showed a slight resistive leakage current curve. After one day, all four electrodes showed a continued decrease in impedance and some low-frequency effects that suggested the presence of leakage current. After two days, however, only pins 11 and 12 still showed any signs of leakage current. All four electrodes' impedance values continued to drop, although at a lower rate. By day five, signs of leakage current had disappeared from all four electrodes, and the impedance levels of all four increased towards the initial value.

### *C. Single-pin tests*

These tests used a slightly modified version of the test setup as was used for the electrode arrays in order to accommodate the physical shape of the single electrodes. The same impedance curve characteristics were expected for the single electrodes, in isolation, as was seen for the electrodes within the arrays.

P2 showed an immediate drop in impedance, but no apparent leakage current effects. The impedance level remained constant through the 40-minute scan. Upon the 60-minute scan, however, a large apparent leakage effect appeared, while high-frequency impedance appeared unchanged. This leakage effect was retained in the 70- and 80-minute scans.

P4, conversely, showed a large leakage current effect immediately upon PBS submersion in addition to a drop in overall impedance. The apparent amount of leakage fluctuated greatly over the following three hours.

P8 exhibited an immediate and strong leakage current effect and impedance drop. Its high-frequency impedance level remained constant for the rest of the test. After five minutes of submersion, the leakage current effect had increased slightly, but did not appreciably change after that time. This pin was left submersed for 24 hours after the initial 2-hour test period to observe the long-term effects of water submersion, with no significant difference seen between the 2- and 24-hour scans.

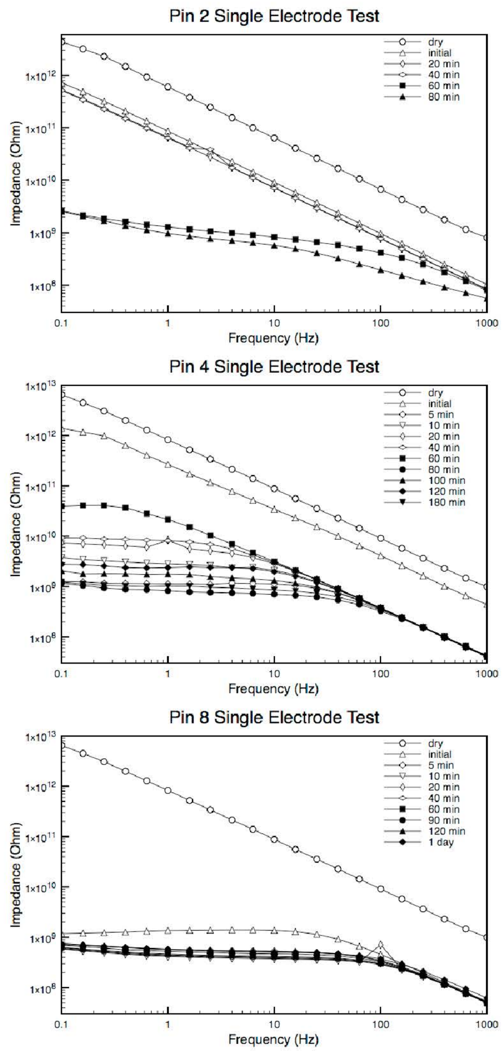


Figure 5. Single electrode test results for pins 2, 4, and 8.

### D. *SEM Photography*

Various physical inconsistencies and potential defects were seen in the parylene C insulation layer when examined via SEM. Suspicious regions were observed on both single pin electrodes P2 and P8 that may have contained fissures and cracks in the insulation. Figure 6 shows a region of such defects on single pin P8.

## IV. DISCUSSION

While the short-term tests do not entire agree with the accelerated tests, both seem to indicate the presence some form of leakage current, and the single-electrodes tests suggest that the location of the leakage is through the electrode shaft insulation The short-term, room temperature, tests all show resistive-type leakage which may be attributed to various insulation failure modes, or combinations thereof, from one array to the next. The long-term tests, on the other hand, show few signs, if any, of leakage current, but there are some possibilities that might explain this discrepancy.

The 1-day scans in all four accelerated stress tests show a slight drop in impedance at frequencies below 1Hz, which could indicate the presence of leakage current. When combined with the lessening of the apparent leakage current effects seen in the short-term wet test of A4 (the same array used in the accelerated stress tests), this shows that leakage currents may appear immediately upon an array's contact with water, but gradually lessen until they are no longer visible at some point between one and two days after submersion in the hot fluid. As shown in SEM photographs of the electrodes, the parylene C layer appears to have defects that may include cracks, pits, and fissures. While these would initially allow water to penetrate the insulation and cause leakage currents, it is possible that at higher temperatures and prolonged water exposure, the surrounding insulation may swell, thus possibly closing the gaps and reducing or eliminating leakage currents seen previously.

While these data are preliminary, they represent one of the first reported studies designed to systematically catalog and quantify the factors that affect implanted electrode longevity. The purpose of this study is to obtain a more comprehensive understanding of the failure mechanisms of multi-electrode arrays used in neural recording. Although not currently conclusive, we have identified several possible failure modes, but further study and investigation is necessary to more completely understand them.

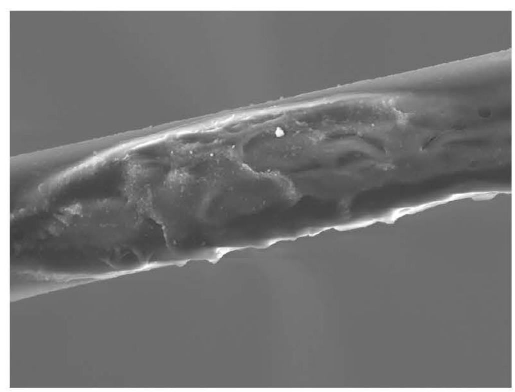

Figure 6. SEM photograph of single electrode pin P8.

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