Low-Impedance, High Surface Area Pt-Ir Electrodeposited on Cochlear Implant Electrodes

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A high surface area, Pt-Ir coating was electrodeposited onto the contacts of Advanced Bionics HiFocus 1j electrode arrays. The coating was imaged using optical and scanning electron microscopy (SEM) and the impedance was directly measured using clinically relevant voltage transients of biphasic pulses as short as 17 μs. The coating, which SEM showed to completely cover the underlying substrate, decreased the polarization impedance of 17 μs and 32 μs pulses by 91% and 93%, respectively.

Cochlear implants have successfully restored functional hearing to hundreds of thousands of individuals; nevertheless, there is still room from improvement. Battery life is limited, tissue encapsulation can insulate the electrode from the target spiral ganglion cells, and the spectral resolution of cochlear implants does not match that of natural hearing. Lowering the impedance of cochlear implant electrodes with a coating, such as electrodeposited Pt-Ir, could help mitigate these issues.

For example, low impedance electrodes can increase the amount of current injected without exceeding polarization potentials that can lead to corrosion, the production of potentially toxic byproducts, or tissue damage. This is useful because the cochlear implantation procedure and the electrode insertion process initiate a foreign body response, resulting in tissue encapsulation around part or all of the electrode array. This tissue capsule can partially insulate electrodes, leading to an increase in impedance and a weaker electric field at target neurons, which then require higher currents to activate.

Reducing electrode impedance could also enable the use of small, high-density microelectrode arrays, including those made with thin-film fabrication technology, which simulations have shown could improve spectral resolution and sound quality. Microelectrodes have not commonly been used for stimulation because their small geometric surface areas are associated with high impedance and—when injecting currents required for neural activation—high polarization potentials, which can cause delamination and corrosion. Lowering the impedance of electrodes would reduce polarization, which would enable the use of high-density microelectrode arrays and open up the possibility of using thin-film fabricated electrodes with their concomitant advantages of batch fabrication and high dimensional precision.

Electrodeposited Pt-Ir is a coating that has been shown to lower impedance and increase charge storage capacity. It combines many of the favorable qualities of other low impedance coatings, while avoiding their shortcomings (Table I). Pt-Ir also exhibits the enhanced mechanical properties of alloys over softer single component metals or brittle ceramics. In this communication, Pt-Ir was deposited onto commercial cochlear implant electrodes for the first time. The impedance was measured and compared to non-coated electrodes directly from waveforms of clinically relevant pulses, which avoids the overestimation of charge storage capacity measurements that may occur when using cyclic voltammetry and is more relevant than using electrochemical impedance spectroscopy (EIS) where low-amplitude, continuous sine-wave stimuli are utilized, and often only a single frequency, such as 1 kHz, is used to compare impedances of different electrode materials.

Experimental
Electrodes.—The Advanced Bionics HiFocus 1j Electrode is a commercially available cochlear implant electrode array consisting of 16 rectangular platinum stimulating contacts. Each contact measures approximately 0.4 mm wide by 0.5 mm long (0.2 mm²). On each array, Pt-Ir was electrodeposited onto 12 electrode contacts using a method described previously and 4 were left uncoated as a control.

Optical microscopy and SEM.—Optical images were taken using a digital microscope (Keyence VHX-1000). Scanning electron microscopy (SEM) and EDS scans were performed using a JEOL JSM-6480 (accelerating voltage: 10 kV, working distance: 9 to 12 mm). Electrodes were grounded to the SEM stage, thus no additional samples were required.

Electrochemical evaluation.—A custom-built Advanced Bionics current pulse generator based on the HiRes 90K implant electronics was used to control current pulses. Voltage transients were captured using a Tektronix DPO 3014 oscilloscope, which measured the voltage across the working electrode (HiFocus 1j contacts) and a large graphite rod counter electrode (Princeton Applied Research, G0091) while trains of biphasic, cathodic-first, charge-balanced pulses were injected through each electrode contact. The electrolyte used was prepared using Type 2 purified water (EMD Millipore Elix Advantage, water).
Table II. Decrease in impedance for biphasic pulses with increasing charge densities.

| Pulse Parameters | Mean Impedance | Decrease (%) | P-value |
|------------------|----------------|--------------|---------|
|                  | Uncoated (n = 3) | Coated (n = 6) |         |
| 17/498/4.2       | 910            | 844          | 7       | 0.081   |
|                  | 550            | 56           | 90      | 0.003   |
| 17/937/8.0       | 925            | 860          | 7       | 0.109   |
|                  | 507            | 46           | 91      | 0.003   |
| 32/498/8.0       | 904            | 843          | 7       | 0.022   |
|                  | 921            | 65           | 93      | 0.006   |
| 32/937/15.0      | 918            | 854          | 7       | 0.039   |
|                  | 752            | 67           | 91      | 0.004   |

resistivity \(>5 \Omega \cdot \text{cm}, \text{TOC} < 30 \text{ ppb}\) and consisted of a physiologically relevant 0.01 M phosphate-buffered saline solution (Sigma-Aldrich, P5368) composed of 2.7 mM KCl, 138 mM NaCl, 1.5 mM KH₂PO₄, and 8.5 mM Na₂HPO₄. All experiments were performed at room temperature (\(\sim 22^\circ\text{C}\)) in open air (dissolved O₂ was present in solution). (Cyclic voltammetry and electrochemical impedance spectroscopy was also performed. Details of which can be found in the supplemental materials.) Four pulse designs within a clinically relevant parameter space \(^{10}\) were tested (Table II). Waveforms were recorded once the waveform shape reached a steady state (generally after 10–20 s).

The access resistance (\(R_a\)) \(^{(1)}\) and polarization impedance (\(|Z_p|\)) \(^{(2)}\) were calculated based on the access voltage (\(V_a\)) and polarization potential (\(E_p\)) taken from voltage transients measured in response to biphasic current pulses \(^{11}\) (also see supplemental material), with \(i_c\) being the amplitude of the cathodic current pulse.

\[
R_a = \left| \frac{V_a}{i_c} \right| \quad [1]
\]

\[
|Z_p| = \left| \frac{E_p}{i_c} \right| \quad [2]
\]

Results and Discussion

Morphology and composition.—SEM (Figures 1a and 1c) and optical images (Figures 1b and 1d) of bare Pt (Figures 1a and 1b) and Pt-Ir coated Pt (Figures 1c and 1d) show the Pt-Ir coating has an anisotropic, rough appearance with microscopic nodules characteristic of electrodeposited Pt-Ir. \(^{8}\) The Pt-Ir coating masked the striations visible on the surface of the bare electrode and did not extend beyond the edge of the base Pt electrode, indicating a well-controlled plating process.

Electrochemical evaluation.—Electrode impedance was directly compared by measuring voltage transients during clinically-relevant biphasic pulses. The \(R_a\) of the coated and uncoated electrodes were not statistically different (Table II). The \(R_a\) is proportional to the \(V_a\) which is the near instantaneous drop in voltage during the leading edge of the pulse train and are nearly identical when comparing coated and uncoated electrodes (Figure 2). This is to be expected because access voltage/resistance is generally determined by the geometric area of the electrode \(^{11}\) and the electrolyte resistivity, which the coating did not change either.

In contrast, \(|Z_p|\)—generally determined by the electrochemical surface area (ESA) and the electrode material \(^{11}\)—was decreased by 91% for the long, low amplitude pulses and 93% for short, high amplitude pulses (Table II). The polarization impedance is proportional to the \(E_p\) defined as the drop in potential between the onset (after the access potential drop) and the end of the cathodic phase of the pulse. For uncoated arrays, the drop appears as a negatively sloped line, whereas the polarization is small enough for the coated arrays

![Figure 1. SEM (a and c) and optical (b and d) images of uncoated (a and b) and coated (c and d) electrodes. The coating darkens the appearance of the electrode (d) due to its rough, nodular morphology (visible on both SEM (c) and optical (d) images). The roughness of the coating masks horizontal striations and reflective morphological features visible on the uncoated SEM (a) and optical (b) images. (Scale bars are 100 \(\mu\text{m}\).)](https://example.com/figure1.png)

![Figure 2. Mean values of voltage transients measured across coated (solid, black line, \(n = 3\)) and uncoated (dashed, red line, \(n = 6\)) electrodes during biphasic pulses of pulse widths and amplitudes. The standard deviation of the voltage transients, which is represented with shading above and below solid and dotted lines, is small and therefore not visible on some curves.)](https://example.com/figure2.png)
that the potential appears to remain constant during the pulse (Figure 2). Eₚ is associated with the electrochemical processes occurring at the electrode interface such as double-layer charging and redox reactions. Since these processes are dependent on electrode material and the ESA of the electrode, Eₚ for the Pt-Ir coated samples is greatly reduced due to the presence of Ir and the coating’s 3-dimensional structure. Many other electrode materials/coatings listed in Table I show low polarization under slow rates of charge transfer (e.g. during cyclic voltammetry or under biphasic stimulation with long pulse widths), but their impedance advantage does not hold up under biphasic pulsing at short pulse widths like those used in the present study. This may be due to the porous nature of other electrode materials, which does not allow sufficient ion flux in and out of pores at fast timescales.

Summary
Pt-Ir was coated onto commercial cochlear implant electrodes and significantly improved their electrochemical performance by decreasing |Zₚ| during clinically relevant pulses. Decreased |Zₚ| may improve sound quality and spectral resolution for future cochlear implants by enabling the use of smaller, more closely packed microelectrodes. In addition, the increase in impedance caused by tissue encapsulation will be less impactful since overall impedance will be lower. Finally, lower impedance electrodes can improve the battery life of the implantable pulse generator (IPG) (or allow for a smaller battery) by using less power to deliver the same amount of current.

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