Compliance supply-limited driving of iridium oxide (AIROF) electrodes for maintenance in a safe operating region.

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Abstract

Although neural stimulating electrodes that use an activated iridium oxide film coating have existed for more than 20 years, the design of electronic circuits to preserve the electrode electrochemical integrity has received only minimal attention. In contemplating the implantation, in humans, of perhaps hundreds of electrodes for use in visual prostheses, it is essential that methods be defined for driving of the electrodes so that deterioration of the AIROF does not occur. We have developed a simple driving technique that limits the cathodic and anodic voltage excursions of any stimulating electrode within the "water window."

1. INTRODUCTION

AIROF electrodes have been proposed for use in neural prostheses within the central nervous system and in the periphery, and research directed at their fabrication and measurement has been reported over the past two decades [1,2,3]. AIROF provides a significantly higher charge capacity, per phase, than other candidate electrode materials [4], particularly those belonging to the noble metal class, e.g. platinum. Since the mechanism of charge injection for metal electrodes is primarily faradaic reactions, it has been long-recognized that anodic and cathodic voltage excursions that drive the electrode potential (relative to Ag|AgCl) beyond –0.6V and +0.8V result in damage to the AIROF film due to the onset of oxidation or reduction of water. Damage to an ARIOF electrode can be virtually immediate and irreversible, frequently taking the form of delamination of the ARIOF film, as shown in Figure 1. Attempts to recover the electrode, in-vitro, or in-vivo, by reactivation are generally unsuccessful. In addition, operation outside of this "water window" may cause significant pH changes within the surrounding tissue. Although the symmetric biphasic constant current waveform has historically been regarded as the standard for driving not only AIROF, but also other metal electrodes, it has recently been shown that arbitrary use of this waveshape may damage the electrodes as the voltage excursions move outside of the water window, and that an asymmetric waveshape can increase the safe charge capacity of the AIROF electrode [5]. We have devised an automatic method of generating an asymmetric constant current stimulating waveform that maintains operation within the water window while maximizing the allowable stimulus charge injection.

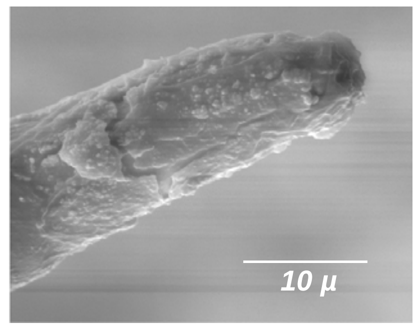

Figure 1. SEM photograph of an AIROF electrode showing delamination due to cathodic voltage excursions below –0.6V vs Ag|AgCl. This damage is irreversible and severely compromises the charge injection capacity of the electrode.

2. METHODS

Typically a biphasic constant current driver consists of an anodic current source, and an cathodic current sink, connected to an anodic and cathodic compliance supply, respectively. Most often, these compliance supplies are in excess of the water window and therefore create the potential for damage to the electrode as the constant current drivers attempt to maintain constant current drive, using only the compliance supplies as a limit.

In an attempt to avoid damage to the electrode, a maximum charge injection limit is typically defined for each electrode and is often based upon the assumed surface area, a percentage utilization of the total charge (as measured by low-frequency CV curves), or is based upon a published figure for the safe charge injection for AIROF. This same strategy is sometimes applied to platinum electrodes as well. The significant point is that the charge injection limit is based upon assumptions for the electrode area, and this defines an *apriori* charge injection limit. This method ignores geometry specific effects, as well as shifts in the access resistance once the electrode is implanted. Consequently, prior studies often report an abrupt onset of electrode damage as the stimulation charge/phase is increased, and we suspect that such damage is caused by voltage excursions that are outside of the water window.

Our approach adopts a rule of cutting back the cathodic current (for cathodic-first stimulation) as necessary to prevent the cathodic voltage excursion from exceeding –0.6V vs. Ag|AgCl. Similarly, during the anodic recharge phase, the anodic recharge current is cutback so as to prevent the electrode voltage from exceeding +0.8V vs. Ag|AgCl. This method is illustrated in Figure 3.

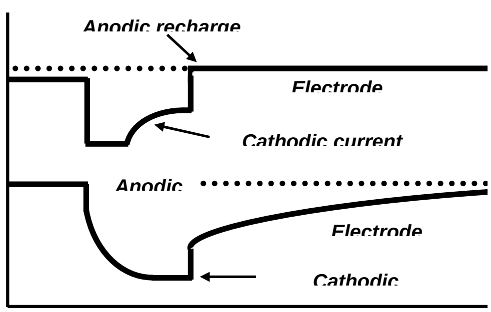

Figure 3. Depiction of electrode current and voltage waveforms for constant current cutback method. Both the cathodic and the anodic drivers automatically reduce the electrode current to prevent voltage excursions outside of the water window.

Figure 4 shows how this rule is practically implemented for a biphasic electrode driver. In actual circuitry, the method is based upon the fact that all electronic current source, and sink, circuits must operate with a finite voltage drop across them. Once the voltage across the circuit is reduced to zero, so does the current. Anodic and cathodic compliance supplies are generated by adding the desired anodic bias, and the desired cathodic limit to a buffered measurement of the reference electrode. Prior to the stimulation pulse, the anodic current source charges the electrode to the anodic bias limit. As the electrode voltage approaches the anodic limit, the anodic current source automatically shuts off due to the reduction in the operating voltage across the current source. Similarly, during the cathodic stimulation pulse, the cathodic current sink can only continue to

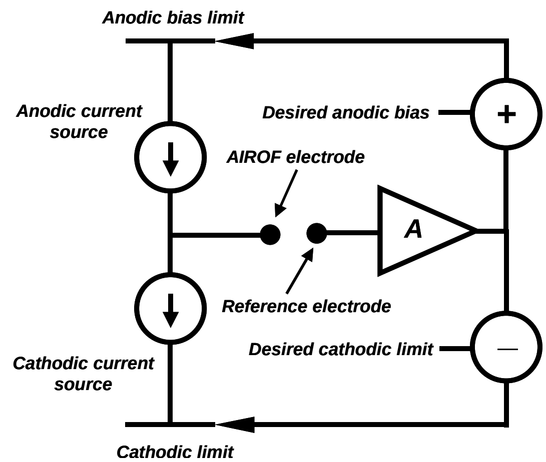

Figure 4. Circuit implementation of the current cutback method. Once the value of the electrode voltage reaches either of the compliance supplies the respective current source automatically cuts backs the current preventing the electrode from exceeding the limit.

sink current while the electrode voltage is more positive than the desired cathodic limit. Once the limit is reached, the cathodic driver automatically reduces current.

If considering the stimulation electrode to be a simple series RC circuit, then use of this method would result in the current being reduced to zero as soon as the capacitor voltage reached the compliance limits. This could, conceivably, uncomfortably limit the charge capacity of the electrode. However, a typical electrode is better characterized by a distributed RC network. Therefore, only a modest cutback in the currents are needed to hold the voltage excursion within the desired window.

It seems almost ridiculously simple that to implement this method, one merely needs to adjust the compliance supplies of *any* biphasic constant current driving circuit. Derivation of the compliance supplies, relative to the reference electrode, is a slight complication. However, by adding a safety margin, one might even use a fixed power supply for each of the compliance supplies.

We fabricated a hardware system that implements the strategy of Figure 4.

Microelectrodes that were fabricated at both the Huntington Medical Research Institutes, and the Laboratory of Neural Control at the NIH were used to determine the effectiveness of the protective method for a variety of electrodes. Electrodes areas ranged between 1000 and 2000 μm^2. Pulsing was done in phosphate-buffered saline (PBS) having a concentration of 0.0125M NaCl, 0.0014M $NaH_2PO_4 \cdot H_2O$, and 0.005M $Na_2HPO_4 \cdot 7H_2O$ at a pH of ~7.3. This reduced PBS concentration (~1/16 of normal) was used to simulate physiologic extra-cellular fluid. The PBS was open to air and thus contained ~0.004M dissolved oxygen. A Ag|AgCl reference electrode was used to monitor the working electrode potential and derive the anodic and cathodic compliance supply limits.

3. RESULTS

A typical waveform set of electrode voltage and current is shown in Figure 5 for a 1000 μm^2 AIROF microelectrode. Under these conditions, with the cathodic cutback, the maximum safe charge injection was 1.86 mC/cm^2. In comparison, had the current pulse been constant, a charge injection of 2.25 mC/cm^2 would have resulted. For only this modest 17% increase, the cathodic excursion would have crossed the –0.6V limit, and electrode the likelihood of electrode damage would have been significantly greater. And, this comparison does not take into account that using a symmetric waveform would not have permitted the anodic bias to be as great as +0.7V, as seen in Figure 5.

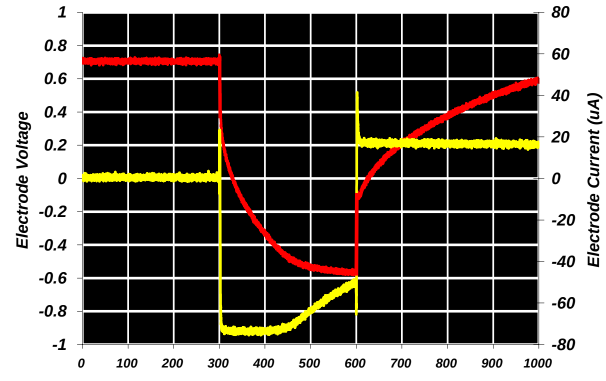

Figure 5. Voltage (red, upper) and current (yellow, lower) waveforms for an AIROF electrode driven with the current cutback method.

4. DISCUSSION AND CONCLUSIONS

One complicating factor arises for electrodes that have excessively high access resistances, or lead designs with large resistances (due to small conductors). For both of these cases, the *IR* drop during stimulation can be substantial and one is tempted to add the *IR* drop to the compliance supply limit.

We believe this approach to be misguided, at least in the case of excessive electrode access resistances. If a substantial portion of the allowable voltage excursion is defined by the access resistance drop, then dynamic measurement of that access resistance becomes crucial to maintaining safe operation of the electrode. Sufficiently accurate computation of the access resistance, on a pulse-by-pulse basis would be required. For the case of lead resistance, the *IR* drop might be more predictable, but would still be a function of the actual stimulus current. In our designs, we ignore the *IR* drops, and adopt a conservative rule of never allowing the electrode voltage to more outside of the water window. One also needs a stable reference electrode. In several tests, we have examined the feasibility of using the counter electrode as a stable reference electrode. For a large area platinum wire, we have found this method to be acceptable for both in-vitro and in-vivo studies, although the open circuit potential of the platinum wire needs to be at least initially measured, and a suitable safety factor added to the derivation of the compliance supplies.

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