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Neural electrode degradation from continuous electrical stimulation: Comparison of sputtered and activated iridium oxide

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ABSTRACT

The performance of neural electrodes in physiological fluid, especially in chronic use, is critical for the success of functional electrical stimulation devices. Tips of the Utah electrode arrays (UEAs) were coated with sputtered iridium oxide film (SIROF) and activated iridium oxide film (AIROF) to study the degradation during charge injection consistent with functional electrical stimulation (FES). The arrays were subjected to continuous biphasic, cathodal first, charge balanced (with equal cathodal and anodal pulse widths) current pulses for 7 h (>1 million pulses) at a frequency of 50 Hz. The amplitude and width of the current pulses were varied to determine the damage threshold of the coatings. Degradation was characterized by scanning electron microscopy, inductively coupled plasma mass spectrometry, electrochemical impedance spectroscopy and cyclic voltammetry. The injected charge and charge density per phase were found to play synergistic role in damaging the electrodes. The damage threshold for SIROF coated electrode tips of the UEA was between 60 nC with a charge density of 1.9 mC/cm^2 per phase and 80 nC with a charge density of 1.0 mC/cm^2 per phase. While for AIROF coated electrode tips, the threshold was between 40 nC with a charge density of 0.9 mC/cm^2 per phase and 50 nC with a charge density of 0.5 mC/cm^2 per phase. Compared to AIROF, SIROF showed higher damage threshold and therefore is highly recommended to be used as a stimulation material.

1. Introduction

Functional electrical stimulation (FES) of biological tissue requires transfer of electronic charge from the electrode to ionic charge in the physiological fluid. There are various neural electrodes which can perform FES, for example, the Utah electrode array (UEA) (Normann, 2007). In order to successfully use these electrode arrays for stimulation in chronic implantation i.e. few years, the electrode material must be both efficacious and safe to use. Efficacy of stimulation primarily means injecting enough charge in the targeted tissue to elicit action potentials. However, in doing so, the electrode itself must not degrade or generate harmful substances or provoke a significant immune response. The active areas of the electrodes must remain stable under the stimulation protocol to achieve a long-term functional response. Achieving this remains a challenge as stimulation protocols that permit prolonged excitation of neurons without injuring the tissue or damaging the electrodes are yet to be developed.

The mechanisms for stimulating induced tissue damage are not well understood. The tissue can be damaged primarily due to three reasons: (1) due to surgical trauma while inserting the penetrating electrodes in the tissue, (2) chemical and mechanical bio-incompatibility of the electrode material, and (3) generation of toxic by-products at the electrode–electrolyte interface during electrical stimulation which cannot be tolerated by the physiological medium (Agnew and McCreery, 1990; Mortimer et al., 1970, 1980; Mortan et al., 1994) and due to prolonged stimulation induced neuronal activity which changes the ionic concentrations of both intracellular and extracellular, for e.g. increase in extracellular potassium, known as 'mass action' theory (McCreery et al., 1990; Horch and Dhillon, 2004).

To reduce the tissue damage from surgical trauma the electrodes can be miniaturized. Selectivity, referred as the ability to stimulate discrete population of nerve fibers without stimulating neighboring population of nerve fibers, may be achieved if one electrode can *communicate* to each fiber. For perfect selectivity the electrode geometry need to be in the range of the nerve fiber. Hence small electrodes or microelectrodes are desirable as far as selectivity

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and surgical trauma is concerned. However, electrode impedance increases with decreases in electrode size. Since noise accompanies impedance (for thermal noise) lower impedance is preferred when recording action potentials. Higher electrode impedance may be acceptable for stimulation but not desirable. Hence there is a trade-off between selectivity and electrode impedance.

Many researchers have indicated from their studies that neuronal damage is electrochemically induced (Lilly et al., 1952; Mortimer et al., 1980; Scheiner and Mortimer, 1990). McCreery et al. (1988) attempted to differentiate between electrochemically induced and neuronal activity induced injury by using platinum (Faradaic) and tantalum pentaoxide (capacitor) electrodes. However, they found equivalent amount of tissue damage under both types of electrodes. All these studies indicates that electrochemically and activity induced injury might not be exclusive.

The guiding design rule to avoid electrode damage while injecting charge is electrochemical reversibility: all processes occurring at an electrode after the application of current pulse are reversed by a second current pulse of opposite polarity. This would eliminate electrode damage and neural damage induced by it. Researchers have showed that the monophasic stimulation waveform is more damaging to the tissue than charge balanced biphasic waveform (Mortimer et al., 1970, 1980; Scheiner and Mortimer, 1990; Pudenz et al., 1975a,b). This can be interpreted as the process occurring during the first phase is reversed during the second phase with ultimate goal of no net charge delivered. While in monophasic all injected charge results in generation of electrochemical reaction products. The electrochemical reversibility is measured by charge injection capacity (CIC). The CIC is the total amount of charge per unit area which may be injected in the electrolyte without damaging the electrodes. The 'safe' CIC is when at no point of time the electrode potential exceeds the water window. The water window is defined as the potential region at which oxidation and reduction of water takes place. If the electrode potential exceeds water window, damage to the electrode can occur in the form of electrode corrosion resulting in dissolution of electrode material in the electrolyte.

For the efficacy of the stimulating electrodes, large CIC is desired. Depending on the electrode material the charge can be injected by double layer capacitance (as in TiN), pseudo-capacitance (as in Pt), or reversible Faradaic reaction (as in IrO_x). However, CIC depends on electrode material, shape and size of electrode, electrolyte used and most importantly on the stimulation waveform.

Fig. 1 summarizes the relationship between injected charge and charge density per phase of the neural electrode with the histological detectable neural injury, for variety of electrodes having different shape, size and geometry, studied in different animals, from various research groups. The tissue damage threshold line is extrapolated from report from McCreery et al. They used Pt and activated iridium oxide film (AIROF) electrodes in the cat parietal cortex (McCreery et al., 1990). Above the extrapolated tissue damage threshold line is a region of unsafe usage of neural electrodes due to neural damage, while below the threshold line is the region of safe usage of neural electrodes. Yuen et al. (1981) studied neuronal damage in cat parietal cortex using Pt disc electrodes. Agnew et al. (1986) used AIROF and Pt/Ir (70/30%) electrodes and implanted them on sensorimotor cortex of the cat. Bullara et al. (1983) used Pt–Ir (30%) electrodes on the ipsilateral pyramidal tract of a cat. To permit selective stimulation of small populations of neurons in close proximity to the electrode, charge injection sites are fabricated with small geometrical areas (cm^2), surface area less than 5×10^{-5} cm^2. The graph also gives a projection of the neural damage threshold for electrodes with different surface areas. Large area electrodes can inject more charge and still be in a safe operating region; while, small area electrodes, with higher charge density must inject less charge to operate in safe regions. However, there is a trade off. Large area electrodes loses selectivity i.e. ability to activate one population of neurons without activating neighboring populations, hence small electrodes are preferred. There are various ways in which neuronal damage can occur, for example, mechanical constriction of the nerve, neuronal hyperactivity due to stimulation or irreversible reactions taking place at the electrode–electrolyte interface (McCreery et al., 1992). This paper investigates the stimulation protocol to prevent the irreversible reactions to take place for iridium oxide electrodes.

For chronic stimulation, stability of the electrodes is very important. In this paper, electrode degradation is investigated and the threshold at which degradation occurs is determined. Typically electrodes are coated with a material which has the ability to inject charge into the extracellular fluid. Iridium oxide (IrO_x) was investigated because it has a large reversible charge injection capacity, thus allowing high charge injection without electrolysis or net dc charge transfer. IrO_x permits significantly higher levels of charge injection compared to Pt or Pt–Ir alloys (Agnew and McCreery, 1990; Weiland and Anderson, 2000). However, the charge injection for iridium oxide depend upon the properties of the IrO_x film,

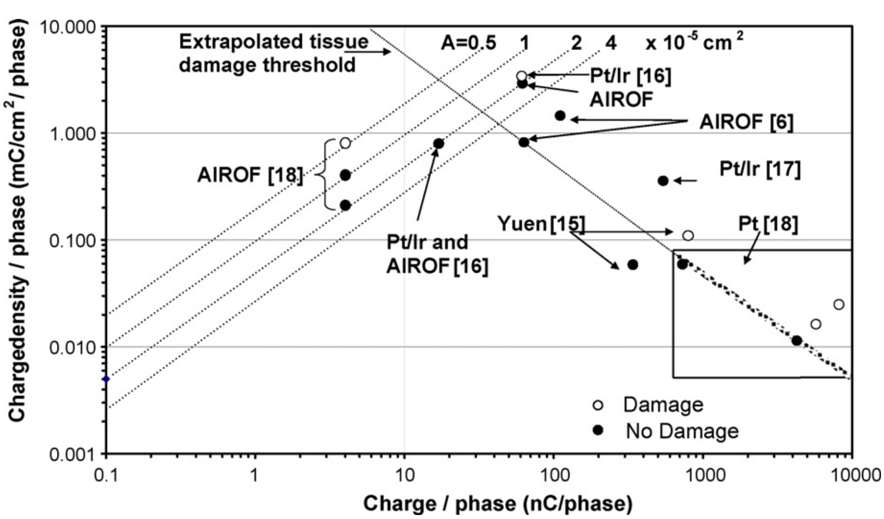

Fig. 1. The effect of charge and charge density on histologically detectable neural injury [Yuen et al., 1981; Agnew et al., 1986; Bullara et al., 1983; McCreery et al., 1990, 2006].