Carbon Nanotube Doped Poly(3,4-Ethylenedioxythiophene) for Chronic Neural Stimulation

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Statement of Purpose: Chronic neural stimulation is widely utilized in neural prostheses to modify, restore, or bypass a damaged or diseased portion of the nervous system by delivering electrical pulses to nearby tissue through neural electrodes. The current stimulation electrode materials do not meet the requirement for many chronic applications. In order to improve the efficacy and biocompatibility of the neural electrodes, conducting polymer poly(3,4-Ethylenedioxythiophene) (PEDOT) has been used to coat the electrodes for neural interface. Conducting polymers exhibit very promising properties, such as low impedance, higher charge capacity, biocompatibility, and drug releasing capability. However, the long-term stability of conducting polymers during chronic stimulation is poor, and they may form cracks or even detach from the electrode surface, which prevents their broad application (Jan E. Nano Lett. 2009; 9:4012-4018). The aim of this work is to improve the chronic stimulation properties of conducting polymer PEDOT by using carbon nanotubes (CNTs) as dopants. As CNTs are highly conductive and mechanically strong, it is expected that the CNT doped PEDOT will exhibit enhanced electrochemical characteristics and mechanical stability.

Methods: The CNT doped PEDOT was electrodeposited on stimulating microelectrode arrays (Second Sight Medical Products, Inc., Sylmar, CA). There are 16 electrodes in a 4 by 4 arrangement on the array, and the exposed electrode surface is 200 micron in diameter. The electrodeposition was carried out in a solution of 1:1 water to acetonitrile containing 2 mg/mL CNTs and 0.2 M 3,4-Ethylenedioxythiophene (EDOT), at a constant current of 100 nA. The CNTs (diameter 20-30 nm) were purchased from Cheap Tube Inc., Brattleboro, VA, and before use they were sonicated in 1:3 HNO_3 and H_2SO_4 for 2 hours to purify the raw CNTs and produce carboxyl groups on the CNTs. For cell culture assays, plastic coverslips (7 by 22 mm) coated with a 40 nm thick layer of gold were used as electrodes, and the electrodeposition condition was a constant potential of 1.0 V. All the electrochemical experiments were performed with a Gamry potentiostat, FAS2/Femostat (Gamry Instruments) with Gamry Framework software, except the long term (two week) stimulation test, where a programmable multichannel stimulator made by Multichannel Systems (STG2008) was used, and a TDS 3014B oscilloscope and the WaveStar program were used to measure and record the voltage excursions.

Results: The PEDOT/CNT coatings on the electrodes were electrochemically characterized using cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS). Judging from the CV curves, the charge capacity of polymer coated electrodes were significantly higher than that of bare electrodes, and several times higher than that of electrodes coated with PEDOT doped with polystyrenesulfonate (PSS) (Cui XT. IEEE Trans. Neural Syst. Rehabil. Eng. 2007; 15:502-508). For the EIS measurement, it is found that the impedance of the microelectrodes can be lowered by more than 2 orders of magnitude with the PEDOT/CNT coatings.

The stability of the PEDOT/CNT coatings during various stimulation conditions was investigated in detail. In the first test, the electrodes were stimulated in phosphate buffer saline (PBS, 10 mM, pH 7.4) using CV from -0.9 to 0.5 V, at a scan rate of 100 mV/s for 3000 cycles. As shown in Figure 1, the PEDOT/CNT coatings are very uniform, and there are no cracks or detachment after the stimulation.

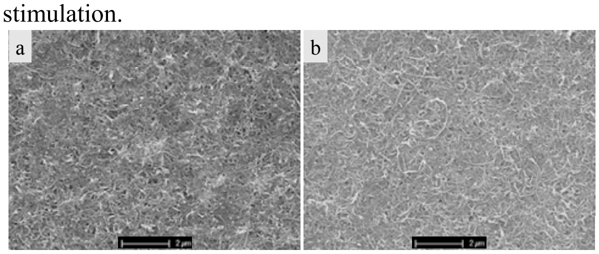

Figure 1. SEM images of the PEDOT/CNT coating on microelectrode before (a) and after (b) electrical stimulation. The coating was electrodeposited at a constant current of 100 nA with a total charge of 40μC.

Next, the coated electrodes were stimulated using a clinically relevant neural stimulation protocol (a biphasic, charge balanced pulse current at 0.35 mC/cm^2 at 50 Hz) for two weeks. PEDOT/CNT exhibited a high charge injection limit of 2.5 mC/cm^2. It was observed that there are no cracks in the film or significant changes in the impedance of the coated electrodes during the long-term stimulation.

Furthermore, cell culture on the PEDOT/CNT coatings indicated that the coatings are non-toxic and the CNTs may guide and promote the growth of neurites.

Conclusions: PEDOT doped with CNTs can form uniform coatings on neural electrodes through electrodeposition, and they can significantly increase the charge capacity and lower the impedance of the electrodes. In addition to their biocompatibility, the PEDOT coatings were very stable during electrical stimulations due to the presence of CNTs, which makes them very promising for chronic neural stimulation.