Electrochemical Analysis of Accelerated Aging of PEDOT-PTS Coated Screen-printed Electrodes

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Abstract: We have developed a deposition method that enhances charge delivery of screen printed electrodes by up to six times through electrochemical deposition of poly (3,4-ethylenedioxythiophene):*p*-toluenesulfonate (PEDOT-PTS). In order to elucidate the effects of PEDOT-PTS deposition on the long-term electrochemical characterization of screen-printed electrodes we characterized electrode stability with cyclic voltammetry and impedance spectroscopy at room temperature and at 47 °C. A deposition current of 0.4 mA/cm^2 guarantees coverage of the working electrode conductive area with no spill of the conductive polymer through the insulating tracks. Control electrodes show charge storage capacity of 0.25 mC. PEDOT-PTS deposited electrodes are stable for over 4 months and present cathodic charge storage capacity of 1.25 mC.

1 INTRODUCTION

The electrode interface continues to be the main puzzle piece in the development of neural coupled devices and implanted sensors. Current challenges are focused on addressing the accumulation of hypertrophic astrocytes, and the development of electrode-investing glial scar tissue (Vallejo-Giraldo et al., 2014), which increases impedance and prevents electrode integration with excitable neural tissues. The development of next-generation electrode technologies is informed by the biological and physico-mechanical considerations of nervous tissues and neural interfaces (Fernandez-Yague, 2015), which has led to advances in the fabrication of high-density microelectrode arrays (Green et al., 2013) and the development of biochemically modified (Kikkawa et al., 2014) and mechanically biomimetic neuroelectrode systems (Ware et al., 2012).

Long-term recording with implanted electrode systems in non-human primates represents a significant bottleneck in the development of brain-computer-coupled devices and of novel medical solutions to neural disorders. Although long-term neural recording has been reported in a handful of studies (Nicolelis et al., 2003) using traditional electrode approaches (parylene-coated microwires),

the controversy of long-term neural recording proliferates due to confounding variables such as handling of the implant, chemical and mechanical properties of implants, surgical technique, and quality of materials implanted, among other fabrication variables.

In order to investigate the mechanisms of electrode failures, *in vitro* experiments are performed with a subset of those variables, under controlled environmental conditions. Previous research from our group, for example, showed that parylene as an insulator would age within 4 months if implanted. However, when parylene is applied in conjunction with ALD (atomic layer deposition) alumina, it demonstrated a four-fold increase in lifetime (Minnikanti et al., 2014). Furthermore, we compared these two kinds of insulations while testing them at relatively high temperatures, or under "accelerated aging" conditions, which allowed us to reliably predict the lifetime of this polymer *in vivo*.

Poly(3,4-ethylenedioxythiophene) (PEDOT) has gained much attention recently (Green et al., 2013, Kim et al., 2014, Mandal et al., 2014), given its biocompatibility, versatility in terms of counter-ion species and high charge storage capacity (Green et al., 2013). Our group has previously investigated several conductive polymers, as well as surface modifications for biological applications (Fernandez-Yague et al.,

2014) and in particular for the development of smart neuroelectrode applications (Mokarian-Tabari et al., 2015).

We hypothesized that we could apply the same principles of testing the material lifetime of electrodes coated with poly(3,4-ethylenedioxythiophene):*p*-toluenesulfonate (PEDOT-PTS) and that electrodeposition of this conducting polymer at the recording surface would enhance their electrochemical properties. In a previous report we have shown that PEDOT was not as stable as iridium oxide when used for stimulation (Peixoto et al., 2009). Here we will address a PEDOT formulation with stable counter-ions and leverage accelerated aging and electrochemical characterization to demonstrate stability of the superficial layers.

In this manuscript we report on the lifetime assessment of such coatings when used for macro screen-printed electrodes. In order to determine stability, we electrodeposit PEDOT-PTS on commercially available low-cost electrodes with a carbon layer as the active material. Those strips, as well as control strips, were subjected to cyclic voltammetry and electrochemical impedance analysis for up to one month at room temperature, and thereafter at elevated temperatures (in our case, 47 °C) for up to three months. The charge delivery capacity of the electrodes is then evaluated, relative to their initial value, and the robustness of coatings determined based on that parameter and on the stability of the modulus and phase angle in impedance profiles.

2 METHODS

Here we describe the utilized substrates, the methods of electrodeposition of PEDOT-PTS, and the electrochemical methods that were utlized in order to characterize the stability of the coatings and of non-coated control samples.

2.1 Substrates and Solutions

Screen-printed paper-based electrodes (Zensor, TE100) were acquired from CH Instruments. Figure 1 shows the as-received electrodes. The counter and working electrode are carbon-based, while the reference electrode is a silver-silver chloride formulation.

All characterizations were performed with electrodes immersed in phosphate buffered saline (Sigma-Aldrich, St. Louis, MO) at 7.4 pH.
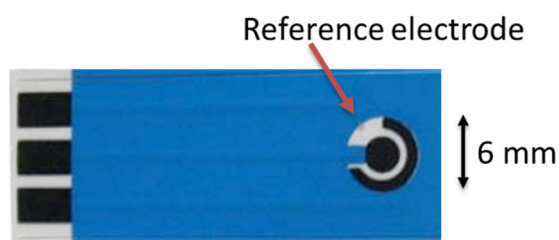

Figure 1: As-received screen-printed electrodes. The active areas are carbon black and silver/silver-chloride. The tabs on the left allow for electrical connection through alligator clips. The active areas are the ring (6mm outer diameter), the center circle (3 mm diameter), and the reference electrode, silver/silver-chloride. The Ag/AgCl is identified by the red arrow. An electrically insulating polymeric cover is identified in blue.

2.2 Electrochemical Deposition

The electrodeposition of PEDOT-PTS films was conducted under ambient conditions. A solution of 0.05 M EDOT (Sigma Aldrich, Ireland) and 0.1 M PTS (Sigma Aldrich, Ireland) was prepared in a 50:50 vol% mixture of acetonitrile and DI water. The electrolyte solution containing the monomeric EDOT was placed in an in-house fabricated electrochemical cell system, as shown in Figure 2. The cell was connected to a Princeton Applied Research electrochemical potentiostat/galvanostat model 2273. The electrochemical apparatus consisted of a four electrode set-up and galvanostatic electrodeposition was performed with 0.03 and 0.64 mA, and providing current densities of 0.4 and 9.014 mA cm^{-2}
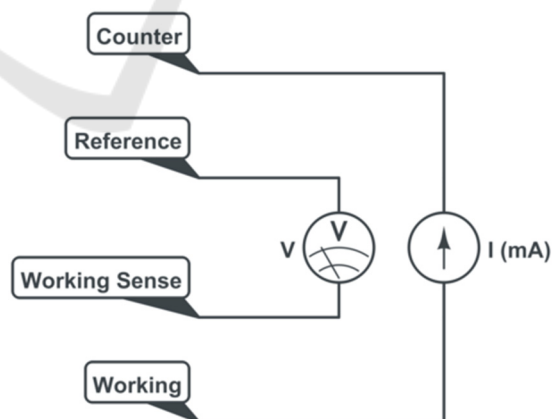

Figure 2: Four-electrode set-up for electrodeposition of PEDOT-PTS onto Zensor TE100 electrodes under galvanostatic conditions. Current is first adjusted according to electrode surface area and then it is applied between working and counter electrodes, while voltage is measured between the sensor (working sense) and reference electrodes.

respectively, over a constant electrodeposition time of 450 seconds. When the deposition was completed, each electrode was soaked in deionized water for 24 h to remove excess electrolyte and unreacted EDOT monomer.

Figure 3 shows magnified images of working electrode following PEDOT-PTS electrodeposition. In this manuscript we discuss results pertaining to the 0.4 mA/cm^2 current deposition, as the higher current showed polymeric coating of the plastic insulation.
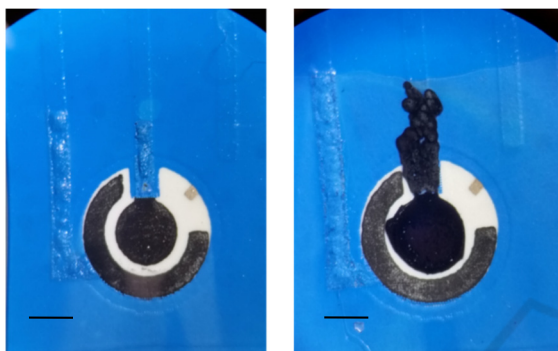
Figure 3: As-deposited screen-printed electrodes. PEDOT-PTS coated electrodes using a current density of 0.4 mA cm^{-2} (left) and PEDOT-PTS coated electrodes using a current density of 9.014 mA cm^{-2} (right). These magnified images show details of the surface of the counter and working electrodes immediately after deposition. Horizontal scale: 3 mm.

2.3 Characterization Techniques

Control electrodes (carbon-based) as well as PEDOT-deposited electrodes were immersed in PBS and characterized over time at 24 °C (room temperature) and at 47 °C. The temperature controller was filled with Aluminium beads and temperature was logged over time with a temperature data-logger. Temperature variation from the heated experiments (47 °C) was within 1 °C over the course of experiment. A common problem with long-term experiments is the evaporation of the media. We resolved evaporation issues as follows: (a) dental cement was used on the cap of vials; (b) Teflon tape used around the threads; (c) a wet environment was created inside a beaker in order to raise the water vapor pressure and to allow for temperature control through a bead bath. Figure 4 shows a schematic of the setup built and used throughout the characterization experiments.

Electrochemical characterization was performed using a 16 channel multiplexer attached to a CHI660D potentiostat (CH instruments, Bee Cave, TX). The potentiostat, the electrodes, and all cables were kept inside a Faraday cage. The potentiostat is
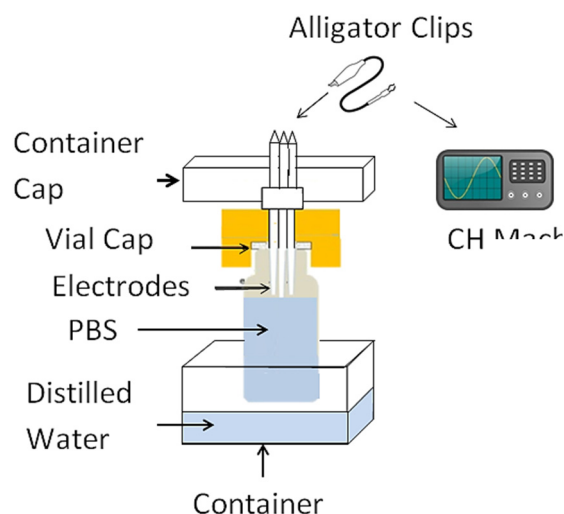

Figure 4: The experimental setup used for long-term characterization of coated and control electrodes. Dental cement was used to seal screen-printed electrodes into electrode cells following PEDOT-PTS deposition. In order to prevent evaporation, vials were filled with phosphate buffered saline. Electrodes were inserted through the vial caps and secured with dental cement. Alligator clips and multi-stranded wires were used to contact the three electrodes to the potentiostat, and the whole vial was kept inside a container with distilled water in order to prevent evaporation. An external environment with saturated humidity guaranteed that no evaporation took place over three months.

connected to a PC, kept outside the cage, through a USB cable. Cyclic voltammetry (CV) is an electrochemical method that entails the application of a voltage between the counter and the working electrode from -0.7 V to 0.7 V while measuring the current through the working electrode, in reference to the silver/silver-chloride electrode. While this test is usually performed continuously, here we ran five periods, at a scan rate of 50 mV/s. Each electrode therefore undergoes five CV cycles and then one EIS test. We have the capability of running up to 16 channels, but we only used 6 of those (3 controls and 3 experimental strips) in order to demonstrate the stability of the coatings for up to two months.

Once a voltammetry cycle was recorded, the current was integrated over half of the period of the voltage applied (for example, from -0.7 V to 0.7 V, or from 0.7 V to -0.7 V) and the charge transferred could be obtained. Because this test was done at low scan rates, it was possible to calculate the *charge storage capacity* of the electrode. More specifically, because integration was applied over the cathodic half of the period, the resulting plot can be referred to as the cCSC (cathodic charge storage capacity), given in Coulombs.
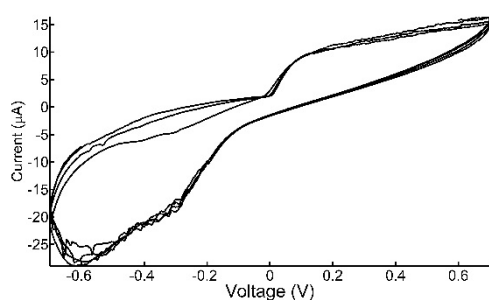
Figure 5: Five cycles of voltammetric spectra of control non-coated carbon electrodes characterized at room temperature, in PBS, with a three-electrode setup, voltage range from -0.7 V to 0.7 V. Current is shown in micro Amperes. Cyclic voltammetry profile was stable for over one week (data not shown).
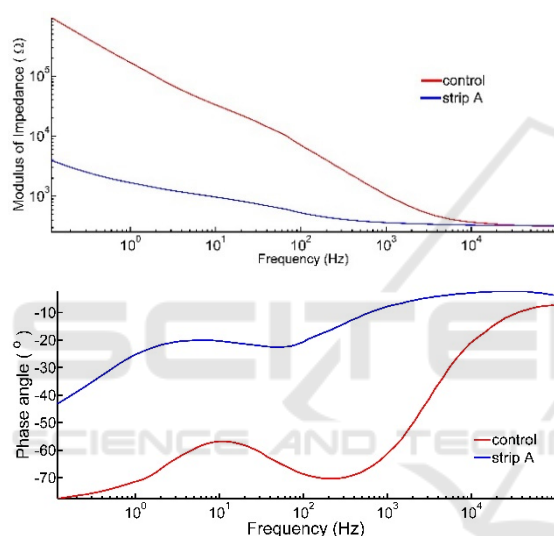

Figure 6: Electrochemical impedance spectroscopy of control and coated electrodes characterized at room temperature, in PBS, with a three-electrode setup. Both impedance modulus (top graph) and phase angle (bottom graph) show a typical profile for carbon black in the control electrode (red curves). For lower frequencies, the electrochemical cell is capacitive (with angles approaching 90 degrees), while for higher frequencies the characteristic resistive phase is seen. This profile was stable over one week (testing period, data not shown). Strip A, in blue, shows lower impedance modulus and a more resistive phase angle than the control electrode.

Electrochemical impedance spectroscopy (EIS) was implemented with a 20 mVrms sinusoidal voltage signal with frequency varying from 0.1 Hz to 100 kHz. Both the modulus and phase were then recorded for one sweep of frequency. Subsequently the electrode was subjected to another cyclic voltammetry (CV) and impedance spectroscopy (EIS) cycle. Throughout 24 hours at least 80 cycles of

these two tests were recorded.

Figure 5 shows a typical CV spectrum for a control electrode. Following one week a similar profile was obtained.

While the CV shows how much charge an electrode could deliver, the impedance profile facilitated the generation of the characteristic circuit component that better describes the interface between the coating and the electrolyte. Figure 6 shows the capacitive nature of the carbon-electrolyte interface at lower frequencies, and the resistive interface at higher frequencies.

3 RESULTS

"As-received" non-coated electrodes (n=10) were used as control substrates in order to determine the stability of the cathodic charge storage capacity. This was calculated as a function of the surface area of the working electrode (7 mm^2), and found to be 0.25±0.10 mC. Due to excessive PEDOT-PTS deposition on the insulated regions when using a current density of 9.014 mA cm^{-2}, we have characterized further only electrodes coated with PEDOT-PTS electrodeposited with a current density of 0.4 mA cm^{-2}, which were assessed for long-term stability *in vitro*.

PEDOT-PTS films deposited at a current density of 0.4 mA cm^{-2} were immersed in PBS and analysed at room temperature for one month, along with three control strips. During this time, approximately 2,000 runs were performed on each electrode. In order to analyze the impedance changes of each electrode, EIS runs for each experimental condition were combined and a mean plot obtained. Figure 7A shows an example of a twenty-four hour interval, for PEDOT-PTS coated electrodes. The stability of the modulus of impedances over time is within one fold for low frequencies (up to 1 Hz) and it is statistically insignificant for frequencies above 10 Hz. Figures 7A and 7B also demonstrate the effects of PEDOT-PTS deposition on the modulus and phase of the low frequency impedance spectrum, reducing the modulus of impedance to less than 10 kΩ at frequencies less than 1 Hz. This is in conjunction with a 30 degree angle on the phase of impedance, indicating a more resistive electrode-electrolyte interface.

While the EIS results demonstrated repeatable profiles, the CV spectra presented noise at voltages above 0.4 V and below -0.4 V. However, the profiles were significantly different to those of the non-coated carbon control electrodes (Figure 4), indicating an
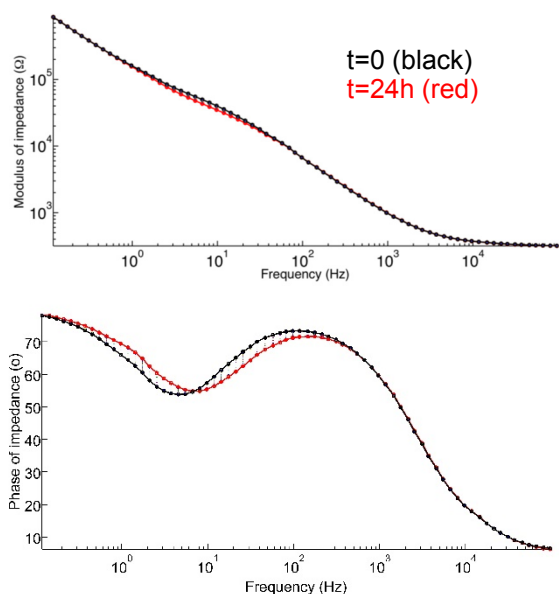
Figure 7: Overlay of electrochemical impedance spectroscopy measurements (modulus) and of phase measurements for PEDOT-PTS coated electrodes. The measurements were obtained at t=0 and after 24 hours at room temperature, in PBS, with a three-electrode setup. The modulus of impedance was stable across all frequencies tested (0.1 Hz through 100 kHz) (top graph). The phase was observed to increase by up to 10 degrees between the beginning and end of the test (lower graph).

increased charge transfer capacity (over 1 mC at room temperature), a higher surface area, and a more electrically active material. Figure 8 shows CVs taken at three different times during a 600-hour run at 47°C. Offsets in current are not considered when calculating the cathodic charge storage capacity. In order to measure cCSC the average current per cycle of the voltage is first subtracted from the current.

After one month of electrochemical analysis at room temperature, both controls and PEDOT-PTS coated electrodes presented profiles which are not statistically different from the profiles recorded during the initial tests (as shown in figure 7 for impedance profiles). In order to force the aging of the electrodes, the temperature of electrolyte was increased to 47 °C and the cathodic charge storage capacity was assessed for up to two months. At this elevated temperature, the main qualitative difference noted was electrical noise. The impact on the EIS and CV however was minimal. In order to quantify stability, we measured the cCSC for over 1,500 voltammetric cycles. Figure 9 shows a summary of these plots obtained from PEDOT-PTS coated and non-coated electrodes. The standard deviation was not plotted on this graph for clarity.
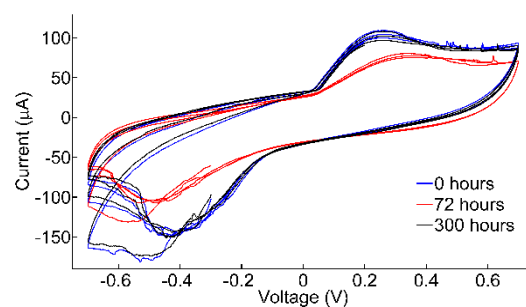

Figure 8: Cyclic voltammetry for PEDOT-PTS coated electrodes characterized at 47°C. Electrodes were immersed in PBS, and the CV recorded using a three-electrode setup, with a scan rate of 50 mV/s. The voltammetry was performed against the reference electrode potential. The blue curve was taken at 0 h (first cycle recorded), red curve at 72 hours, and black curve at 144 hours.

Each electrode was characterized approximately 3 times per hour, for up to 500 hours. There were two interruptions due to power outages, one around the 300-hour mark, and one around the 420-hour mark. This means that we are reporting on approximately 400 hours (non-consecutive). Approximately 1,000 files were generated per electrode and each files was used to extract one cCSC, which was then plotted along the time axis (Figure 9). The mean and standard deviation of the cCSCs for control and PEDOT-PTS electrodes was recorded as 0.26±0.12 mC; 1.25±0.30 mC, respectively.
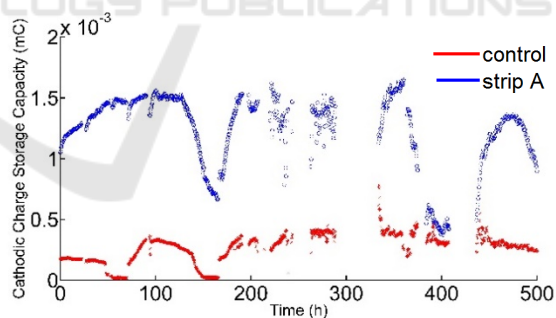

Figure 9: Cathodic charge storage capacity over time for control (red) and PEDOT-PTS coated electrodes (blue and black). The charge storage capacity indicates the stability of the cyclic voltammetry through a combined mean data point. Each number corresponds to a full cycle of a CV performed on the electrode from -0.7 V to 0.7 V at 50 mV/s, against a reference electrode. These experiments were performed in PBS held at 47°C.

4 DISCUSSION

Recently, several groups have demonstrated the

successful deposition of PEDOT-PTS on Platinum substrates for electrical stimulation in neural prosthetics applications (Green et al., 2012, Green et al., 2013) or as conductive films electro-sprayed onto glass substrates (Kim et al., 2104). To our knowledge, this is the first report of a PEDOT-PTS film successfully deposited on Carbon substrates, on commercially available screen-printed electrodes.

We have successfully designed a coating protocol for PEDOT-PTS thin films that can be adjusted in order to obtain varying charge delivery capacities. The charge storage capacity of the films showed a five to seven fold increase over the commercially available carbon coating, and given the surface area of the working electrode (7 mm^2), and the highly non-uniform surface, the cathodic charge storage capacity of 0.25 ± 0.10 mC was not surprising. A usual side effect of thin film coatings, and in particular for PEDOT electrodes, is the splitting of layers, also known as delamination, over time. Factors that affect delamination are the dynamic range of the voltage applied during CV tests, the temperature at which the characterizations are performed, the surface roughness and the electrostatic interaction at the material interface.

Delamination can usually be visualized on the surface of the electrode seen as cracks when it is substantial (Green et al., 2012), and it is a significant concern in implantable applications since coating technologies can be important to preserve biocompatibility during chronic recording or stimulation (Vallejo-Giraldo et al.). Critically, when during the onset of delamination, electrochemical methods can point to subtle or microscopic defects that are not readily found microscopically. With the combination of cyclic voltammetry and impedance spectroscopy profiles, it was possible to ascertain over time, the stability of the interface between the working electrode or the electrode coating and an electrolyte.

By characterizing electrodes over several months we demonstrated that the charge and the impedance can vary around a mean value but remained stable *in vitro*. Robustness of the PEDOT-PTS could then be demonstrated at room temperature and when subjected to accelerated aging at elevated temperatures. In can be hypothesized that for applications utilizing implantable PEDOT-PTS coated electrodes, a similar robust behavior can be expected. The original motivation for electrochemical analysis at 47 °C was derived from the hypothesis that in general, for every 10 degree increase in temperature, it can expected that the lifetime of the polymer will decrease by a factor of two. In other

words, given that 10 days is the mean time to failure cited in the literature for implanted PEDOT-PTS coatings (Green et al, 2012), it could be expected that the carbon-based electrodes investigated in this study would fail within 5 days.

The robustness of the screen-printed electrodes was a further unexpected result observed in this exploration and the polymeric insulating coating did not delaminate over the course of three months (total test time) indicating the potential applications of these cost-effective devices for implantable devices.

Future studies will focus on the miniaturization of the deposition area and on validating the stability of PEDOT-PTS coated electrodes in neuronal-glial culture maintained for over three months, while leveraging the electrodes for stimulation and recording of extra-cellular activity.

5 CONCLUSIONS

PEDOT-PTS films, when deposited on Carbon-based substrates, enhance the electrode-electrolyte interface through increasing the charge delivery with a constant surface area. The potential of this coating approach for neuroelectrode applications is further validated through the coating persistence and delamination was not observed for up to two months in age-accelerated conditions. We intend to test miniaturized electrodes with the same coating process, and with neuronal-glial cultures, in order to further characterize PEDOT-PTS for biological applications.

ACKNOWLEDGEMENTS

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