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Surface Roughness-Dependent Corrosion: Implications for Cochlear Implant Reliability

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Abstract: The corrosion behavior of platinum electrodes in cochlear implant (CI) systems is a critical factor affecting their long-term functionality. This study investigated the influence of the surface roughness of the platinum electrodes on their corrosion behavior. The results of *in vitro* experiments indicate that higher surface roughness tends to accelerate corrosion by providing numerous initiation sites. Although the electrochemical measurements of platinum electrodes with different surface roughnesses showed only slight differences in terms of shifts in potentials and higher corrosion current densities, data from the literature suggests an enhanced charge capacity with rougher surfaces. These findings contribute to an understanding of the failure mechanisms of CIs and can ultimately help to improve the design and durability of CI systems.

Keywords: platinum, cochlear implant, corrosion, cyclic voltammetry, polarization measurement, roughness

1 Introduction

The use of cochlear implants (CI) to treat people with severe to profound deafness is state of the art [1]. Comprising two main components, the system includes an external part worn behind the ear for the conversion of acoustic waves into electrical signals. The signals are then transmitted to the auditory nerve through direct electrical stimulation via an electrode array located inside the cochlea, enabling the perception of sound [2]. A commonly used electrode material is platinum, which is considered biocompatible and inert, and has been used in various biomedical applications due to its good electrical conductivity, radiopacity, and high corrosion resistance [3]. However, previous *in vitro* studies have shown that electrical stimulation in the body can cause morphological changes due to material loss caused by corrosion and chemical changes due to deposits on the electrode surface of the platinum electrodes [4][5]. Post-mortem examination of the temporal bones of cochlear implant recipients revealed platinum particles in the fibrous environment of the implant, whereas optical analysis of explanted electrodes revealed signs of surface corrosion in the form of pitting [6][7].

The relationship between corrosion and the functionality of the implant system is the subject of ongoing research. Animal studies performed by Barrese et al. [8] highlighted platinum corrosion of intracortical electrodes as a potential cause of drops in impedance, possibly attributed to surface changes induced by pitting corrosion [9]. Inflammatory reactions, foreign body reactions, and the formation of fibrous capsules around the implant lead to an increase in impedance, which then is typically compensated by stronger electrical impulses to achieve the same perceived stimulation of the nerve cells [5][3][10]. The level of stimulation current, in turn, influences the response of the tissue and the extent of platinum corrosion itself [9][11].

External influences such as the electrical excitation of the platinum electrodes and the composition and pH of the surrounding medium has a major impact on platinum corrosion. However, the material properties of platinum also play a critical role in rate of the corrosion reactions. These include the material's microstructure and the impurity content of the electrode material, as well as the surface structure, which includes roughness. In general, metals that have smoother surfaces tend to exhibit lower corrosion rates due to reduced attack surface area [12]. In this context, it is important to note that microscopic analyses prove that even the electrode surfaces of brand-new commercial CIs can exhibit relatively high roughness as well as microscopic dents due to the mostly manual manufacturing process.

In order to determine the influence of surface roughnesses on the corrosion behavior of platinum, investigations were

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carried out on non-stimulated platinum samples with varying degrees of roughness.

2 Material and Methods

2.1 Optical roughness measurement

This study used platinum samples with 99.9% purity (EVOCHEM Advanced Materials) measuring 10 mm x 10 mm x 0.1 mm to provide the desired variation in surface roughness. To prevent surface damage from the heat generated by friction during grinding, all samples underwent wet grinding with silicon carbide paper and cleaning in an ultrasonic bath with ethanol. Emery paper with grits of 120, 320, 800, and 1200 (Cloeren Technology GmbH) adjusted the surface roughness.

A 3D laser scanning microscope (VK-9700 Keyence) based on a confocal measuring principle determined the surface roughness parameter S_a of the samples according to DIN EN ISO 25178.

2.2 Cyclic Voltammetry

The cyclic voltammetry was conducted at 37 °C using a three-electrode setup. A saturated Ag/AgCl electrode served as the reference, while platinum was employed both as the counter and the working electrode. The investigations were carried out utilizing a potentiostat from GAMRY Instruments (Reference 600). Before the measurement, the samples underwent a cleaning regime according to the method described by Hibbert et al. [13]. The artificial perilymph, which was used as the electrolyte, was prepared following the recipe proposed by Prasad et al. [14]. The setup was aerated to maintain a constant oxygen concentration in the electrolyte. To minimize environmental disturbances, all experiments were conducted within a Faraday cage.

For the cyclic voltammetry tests, a scan rate of 0.5 V/s was employed. The voltage limits were set to -1.1 V (lower limit) and 1.4 V (upper limit).

2.3 Polarization Measurement

Polarization measurements were conducted to determine the corrosion rate and corrosion current density depending on the surface roughness. The measured data were analyzed using Tafel plots. A micro-cell with a potentiostat (Metrohm Autolab) was used for the polarization measurements. The reference, counter, and working electrode were the same as in the cyclic voltammetry tests, and artificial perilymph was again used as the electrolyte. In these tests, not the whole sample was in contact with the electrolyte, but only a small area, see fig. 1. For these measurements, a potential of ± 0.3 V from the open circuit potential was applied at a scan rate of 10 mV/s. Measurements were taken at three different areas from each sample.

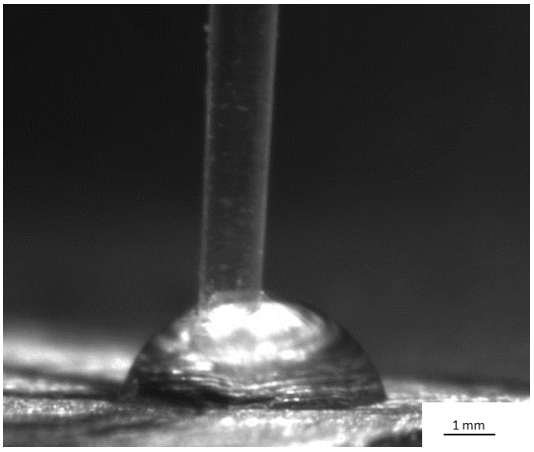

Fig. 1: Drop of the artificial perilymph on the platinum foil for the measurement with the micro-cell

3 Results

The surface roughness data was measured using the confocal laser microscope are summarized in Table 1.

Tab. 1: Surface roughness of different platinum samples.

Sample	Emery paper grit size	S_a in µm
A-120	120	2.13
B-320	320	0.75
C-800	800	0.22
D-1200	1200	0.21

The differences in roughness cover a wide range to mimic both smooth surfaces and those featuring dents or scratches induced by manual handling.

3.1 Cyclic Voltammetry

The cyclic voltammograms in Figure 2 show that the expected characteristic peaks are present but show only small changes upon varying the surface roughness. Sample B-

320 shows the largest reduction peak and the largest hydrogen desorption. The oxygen oxidation regions are also similar. The hydrogen adsorption and desorption area are almost symmetrical for the samples, and thus they have similar electrochemically active surfaces with marginal differences.

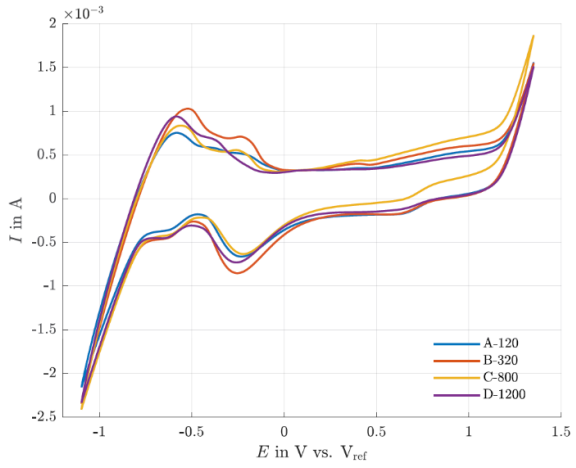

Fig. 2: Cyclic voltammograms of the platinum foils with different surface roughness in artificial perilymph

3.2 Polarization Curve

The polarization curves show a clear tendency for the corrosion potential to increase and a decreasing corrosion current density with decreasing roughness, cf. Figure 3. Three measurements were made for each sample, as in cyclic voltammetry. The differences between the individual measurements were found to be marginal and reproducible.

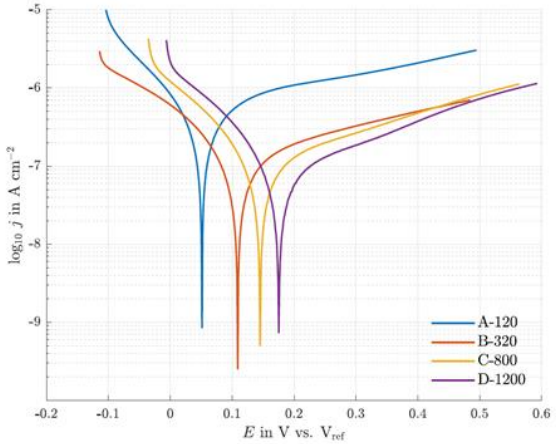

Fig. 3: Tafel plots of the platinum foils with different surface roughness measured using a micro-cell with artificial perilymph

The Tafel plots show that samples B-320 to D-1200 have similar corrosion current densities, and a slight shift in the corrosion potential from 0.11 V to 0.18 V occurs with decreasing surface roughness. The difference between sample A-120 and the other platinum foils is more evident. The corrosion potential here is only 0.05 V, and the corrosion current density is substantially higher.

4 Discussion

The electrochemically active surface area ($\boldsymbol{A_{Pt}}$) in cyclic voltammetry measurements has a linear relationship to the amount of charge in hydrogen adsorption ($\boldsymbol{Q_H}$):

$$\boldsymbol{A_{Pt}} = \frac{\boldsymbol{Q_H}}{\boldsymbol{210\ \frac{\mu C}{cm^2}}} \qquad (1)$$

Aurian-Blanjeni et al. showed a linear relationship between different roughness settings on iridium oxide electrodes and the amount of charge. Thus, the amount of charge should increase with increasing roughness. Their work suggested that only line roughness showed a consistent linear increase. The results of their study show clear differences in surface roughness only when the variations are significant [15]. In the work of Weremfo et al., a higher surface roughness was shown to be useful for increasing charge storage capacity, making it more suitable for nerve stimulation [16]. A similar result was presented in the work of Green et al. [17]. Roughened electrodes showed improved charge transfer properties, which is relevant for medical applications such as cochlear implants. In addition, Márton et al. showed that rougher surfaces increase the effective surface area and lower the impedance [18].

In addition to the benefits of electrical stimulation, Daubinger et al. demonstrated the influence of roughness on nanostructured platinum electrodes. Increasing the roughness can lead to changes in the electrochemical behavior and potential shift by affecting the electrochemical potential between the electrode and the electrolyte. However, increased roughness provides more sites for corrosion initiation and propagation [12]. Similar effects were shown in the work of Gencoglu et al. Surface irregularities can create localized areas of high stress, leading to the spread of corrosion. The rough surface also affects the diffusion of corrosive substances, resulting in the accelerated formation of pits or crevices [4]. These results were also clearly visible in this study from the polarization measurements. The

sample with the highest roughness showed the worst corrosion behavior regarding corrosion potential and current density. These parameters improved with decreasing roughness. Due to the significant difference in roughness between sample A-120 and the other platinum foils, a shift in the curves was observed. The other samples showed minimal differences in roughness and negligible effect on the Tafel plots. Thus, an optimal balance must be found between a rough surface for better charge storage capacity and a smooth surface for less corrosion. Specifically, handling-induced defects appear to be critical as these locally create conditions that should be close to those inferior performing sample A-120.

5 Conclusion

This study investigates the influence of surface roughness on the corrosion behavior of platinum foils. The main results are summarized as follows:

1. In general, higher surface roughness leads to a shift towards lower potentials and higher corrosion current densities in the Tafel plot. This increase is attributed to the increased number of corrosion attacks.
2. The effect of roughness observed in the polarization experiments does not appear in the cyclic voltammograms, which probe charge capacity instead of corrosion resistance.
3. Handling-induced surface roughness could critically reduce local corrosion resistance.

Author Statement

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Informed consent: Informed consent has been obtained from all individuals included in this study.

Ethical approval: No tests were carried out on humans or animals

References

[1] Lenarz T 2017 Cochlear Implant – State of the Art *Laryngorhinootologie* **96** S123-S151

[2] Dazert S, Thomas J P, Loth A, Zahnert T and Stöver T 2020 Cochlear Implantation *Deutsches Arzteblatt international* **117** 690–700

[3] Sinitsyna O, Paralikar P, Pandit R and Rai M 2018 Platinum in Biomedical Applications *Biomedical Applications of Metals (Springer eBook Collection)* ed M Rai *et al* (Cham: Springer International Publishing) pp 151–65

[4] Gencoglu A and Minerick A 2009 Chemical and morphological changes on platinum microelectrode surfaces in AC and DC fields with biological buffer solutions *Lab on a chip* **9** 1866–73

[5] Wissel K, Brandes G, Pütz N, Angrisani G L, Thieleke J, Lenarz T and Durisin M 2018 Platinum corrosion products from electrode contacts of human cochlear implants induce cell death in cell culture models *PLOS ONE* **13** e0196649

[6] Nadol J B, O'Malley J T, Burgess B J and Galler D 2014 Cellular immunologic responses to cochlear implantation in the human *Hearing Research* **318** 11–7

[7] O'Malley J T, Burgess B J, Galler D and Nadol J B 2017 Foreign Body Response to Silicone in Cochlear Implant Electrodes in the Human *Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology* **38** 970–7

[8] Barrese J C, Aceros J and Donoghue J P 2016 Scanning electron microscopy of chronically implanted intracortical microelectrode arrays in non-human primates *J. Neural Eng.* **13** 26003

[9] Shepherd R K, Carter P M, Dalrymple A N, Enke Y L, Wise A K, Nguyen T, Firth J, Thompson A and Fallon J B 2021 Platinum dissolution and tissue response following long-term electrical stimulation at high charge densities *J. Neural Eng.* **18** 36021

[10] Wilk M, Hessler R, Mugridge K, Jolly C, Fehr M, Lenarz T and Scheper V 2016 Impedance Changes and Fibrous Tissue Growth after Cochlear Implantation Are Correlated and Can Be Reduced Using a Dexamethasone Eluting Electrode *PLOS ONE* **11** e0147552

[11] Shepherd R K, Carter P M, Enke Y L, Thompson A, Flynn B, Trang E P, Dalrymple A N and Fallon J B 2020 Chronic intracochlear electrical stimulation at high charge densities: reducing platinum dissolution *J. Neural Eng.* **17** 56009

[12] Daubinger P, Kieninger J, Unmüssig T and Urban G A 2014 Electrochemical characteristics of nanostructured platinum electrodes--a cyclic voltammetry study *Physical chemistry chemical physics : PCCP* **16** 8392–9

[13] Hibbert D B, Weitzner K and Carter P 2001 Voltammetry of Platinum in Artificial Perilymph Solution *J. Electrochem. Soc.* **148** E1

[14] Prasad S *et al* 2020 Radixin modulates the function of outer hair cell stereocilia *Commun Biol* **3** 792

[15] Aurian-Blajeni B, Kimball A G and Robblee L S 1987 Correlation Between Charge Storage Capacity and Morphology *Journal of The Electrochemical Society*

[16] Weremfo A, Carter P, Hibbert D B and Zhao C 2015 Investigating the interfacial properties of electrochemically roughened platinum electrodes for neural stimulation *Langmuir : the ACS journal of surfaces and colloids* **31** 2593–9

[17] Green R A, Toor H, Dodds C and Lovell N H 2012 Variation in Performance of Platinum Electrodes with Size and Surface Roughness *Sensors and Materials* 165

[18] Márton G, Bakos I, Fekete Z, Ulbert I and Pongrácz A 2014 Durability of high surface area platinum deposits on microelectrode arrays for acute neural recordings *Journal of materials science. Materials in medicine* **25** 931–40