Morphological and Electrochemical Properties of an Explanted PtIr Electrode Array after 15 Months *In Vivo*

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***Abstract*— We investigated the morphological and electrochemical properties of an explanted laser-machined 32 channel electrocorticogram (ECoG) electrode array made of platinum-iridium and silicone rubber. It was connected to a wireless brain-computer interface (BCI) and implanted in a sheep for more than 15 months. Recordings and stimulations of cortical activity were conducted over the whole period on a regularly basis. Currently, this is the longest *in vivo* study for this type of ECoG electrode array. Results were compared with an unused electrode array of same dimensions, material and production method. Visual inspections revealed no significant material alterations, despite organic residuals which could be easily removed though. Electrochemical impedance measurements also attested proper long-term stability of magnitude and phase, the difference between explanted electrode contacts and those of the unused array were found negligible.**

I. INTRODUCTION

In 2012 we implanted the first version of our BCI Braincon, which was capable of long-term recording and stimulation of cortical activity [1], in a large animal model. A sheep (ovis orientalis aries) was suggested in former studies described in the literature on e.g. epilepsy, stroke or deep brain stimulation [2–4]. The BCI consisted of the implant unit which could send neurological data wirelessly via infrared light through the sheep's skin. Powering was achieved by means of radio-frequency inductive coupling, similar to common cochlear implants. The ECoG electrode array was manufactured utilizing a well-established, laser-based process which is described elsewhere in detail [5]. The utilized materials where medical grade silicone rubber and platinum-iridium (PtIr) 90/10 for conductive elements. PtIr was chosen for its superior charge injection capacitance over e.g. pure platinum [6] and higher mechanical strength. An intermediate parylene C layer was used for further improved mechanical stability of the whole array [7]. The ECoG array possessed 32 contact sites, where 16 where assigned to recording functionality and 8 where utilized for stimulation. Additionally, two rows of seven connected electrode sites were shorted and used as common reference contacts. All electrode channels were hard-wired to the implant unit, whose contact sites either provided routing to recording or stimulation electronics. Hence, no functionality switching of individual contacts was possible. Measurements were undertaken on a regularly basis. The sheep was trained under veterinary guidance to allow cortical recordings in wake state over a period of more than ten months. Four measurements under anesthetic were performed after 29, 114, 281 and 308 days, where also electrical stimulation of cortical areas was conducted over selective stimulation channels. Eventually, after 463 days the BCI was explanted.

The focus of this paper lies on the characterization of the explanted ECoG electrode array after more than 15 months *in vivo*.

II. MATERIALS AND METHODS

Contact sites were inspected visually and by scanning electron microscopy (SEM); electrical impedance spectroscopy (EIS) was conducted to identify possible alterations.

A. Preparation of explanted ECoG electrode

The cable which connected implant and ECoG electrode array was cut in the middle (d = 25 cm) to allow an analysis of the individual components. The front end of the array (Fig. 1 - red), which was envisaged for visual inspection was separated with a precise cut, utilizing a picosecond laser (wavelength 355 nm, model Rapid 10, Coherent Inc., Santa Clara, CA, USA). The parting line went through the second top row of the recording electrode sites. Minimizing thermal side-effects [8], the picosecond laser cut allowed a clear analysis of the electrode's cross section. Debris related to the cutting was removed after laser treatment utilizing a microbrush and ethanol. Organic residuals accumulated over 15 months *in vivo* were removed by applying an enzyme driven trypsinEDTA solution (Sigma-Aldrich Chemie GmbH, Steinheim, Germany) to the array. The mixture was chosen as an alternative to the acutase solution proposed by Benvenuto et al. [9] for cleaning electrodes after *in vivo* application. The liquid was dripped onto the array's side of the opened contacts, left for five minutes and to be eventually removed by careful wiping with a microbrush. Subsequently the cleaned area was rinsed with ethanol and deionized (DI) water. To compare the effectiveness of the procedure as well as a possible impact of organic material on electrical measurements, only one half of the ECoG array was cleaned (Fig. 1 - blue). The explanted ECoG as well as an unused PtIr electrode array with exactly the same pad (ø = 1,1 mm) and track geometry was inspected by means of optical microscopy and SEM. Top view and cross sectional images were taken with both methods.

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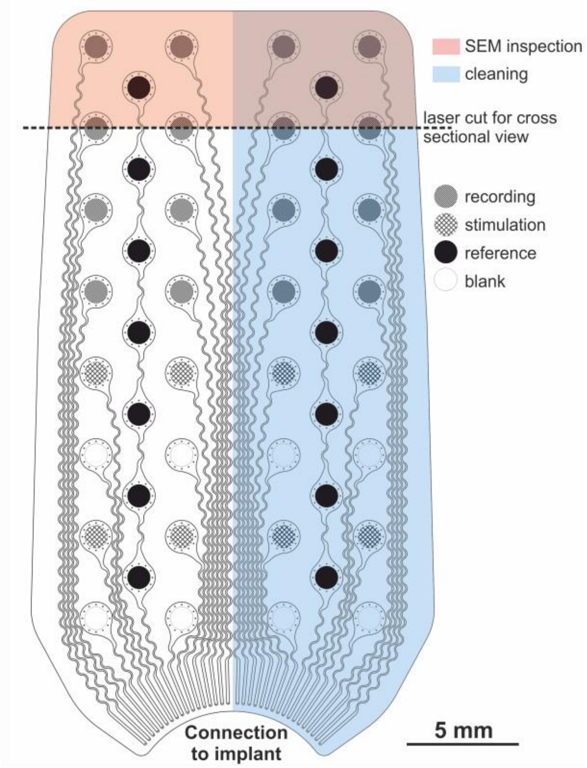

Figure 1: Sketch of the explanted ECoG electrode configuration, including pad assignments. The area which was laser-cut and analyzed in a SEM is marked in red, the blue area received extensive cleaning.

B. *Electrical impedance spectroscopy*

The electrical properties of the electrode contacts were investigated by electrical impedance spectroscopy. A sine wave, 10 mV amplitude was swept in the frequency range from 0.1 Hz to 10 kHz. A three electrode setup was utilized for measurements, consisting of the electrode under test as working electrode (WE) connected to an Autolab PGSTAT-128N impedance/gain phase analyzer (Metrohm GmbH, Filderstadt, Germany), an Ag/AgCl reference electrode (RE) and a platinum counter electrode (CE). All electrodes were submersed in phosphate buffered saline (PBS) solution at room temperature (approx. 22°C). Prior to measurement the electrode arrays were dipped in ethanol to ensure proper wetting and to avoid air bubbles on the contacts. Data acquisition was performed with the software tool Nova, Version 1.9 (also Metrohm GmbH).

The unused electrode array as well as the explanted ECoG were characterized. To establish a proper electrical connection to the explanted electrode, 10 cm of silicone tubing were removed from the severed implant cable. A centimeter of polyesterimide insulation was stripped from each individual MP35N wire to bare the contact site. The new and unused electrode array was connected via single MP35N wires (l = 25 cm) which were welded to the electrodes PtIr connection end.

III. RESULTS

Many tracks of the explanted electrode array were broken at measurement date. Handling during explantation may have caused further contacts to break in addition to those which were already damaged while the system was still implanted. Consequently electrical data could be obtained from seven functional contact sites only. However it was possible to obtain electrical data from at least one contact of each type (recording and stimulation from each electrode side, respectively). This is especially noteworthy for the two reference electrodes which consisted of seven connected contact sites, but possessed broken conductive paths behind the first contact site. Hence electrical characteristics were comparable to all other contacts since the geometrical area of the transition metal to electrolyte was equal.

A. *Visual inspection*

A comparison of the explanted electrode array to the unused grid showed no alterations of the contact surface (Fig. 2) as well as no progressed layer delamination between different materials, as SEM images of cross sections revealed (Fig. 3). Presumable organic residuals could be removed easily (Fig. 2 - b)).

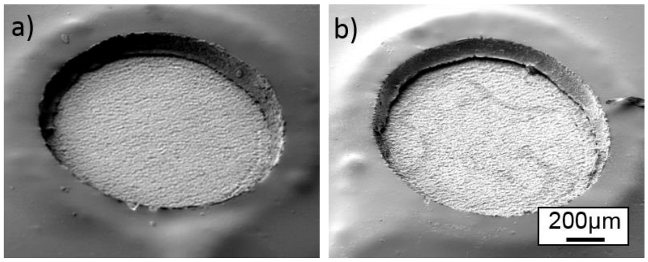

Figure 2: SEM images of electrode contact sites. a) contact on the unused new ECoG electrode array, b) contact on the explanted and cleaned array

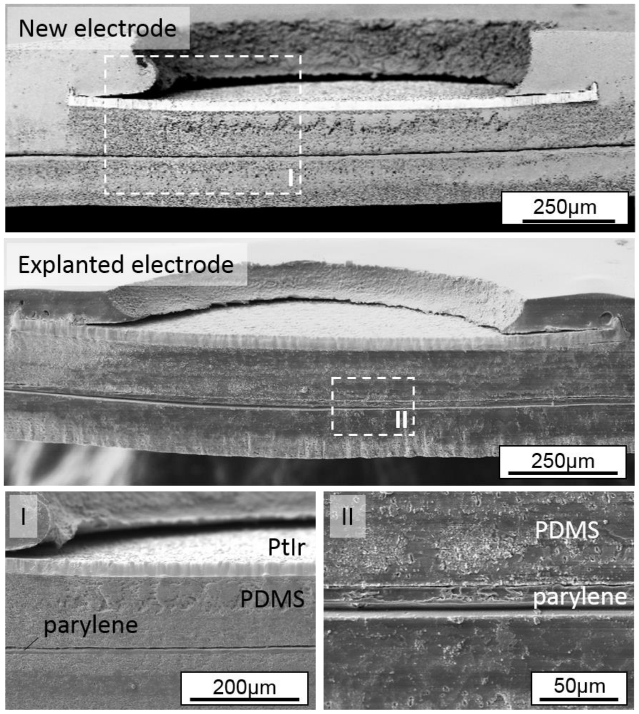

Figure 3: SEM image comparison of cross sections of an electrode contact on the unused (top) and on the explanted electrode array (middle). Bottom images show details of the cross sections referring to insets I and II.

B. EIS measurements

The remaining electrodes sites of the explanted electrode array showed only minor changes in impedance magnitude and phase compared to the unused ECoG (Fig. 4 and Fig. 5). The access resistance R_a was found to be 500 Ω, the corner frequency f_g was 3.3 kHz for almost all contact sites which were still functional. ECoG contacts which were treated with trypsin-EDTA solution showed no changed curve progression compared to non-cleaned contacts. The only exception was the remaining reference site on the left hand side of the array (compare Fig. 1) where the corner frequency was shifted to the left and the access resistance was increased ($f_g = 200Hz$, $R_a = 6.1\ k\Omega$). This fact was most likely due to residuals sticking to the electrode's active surface, which could be seen under the microscope. Since the active area was reduced the curve shift seemed expectable.

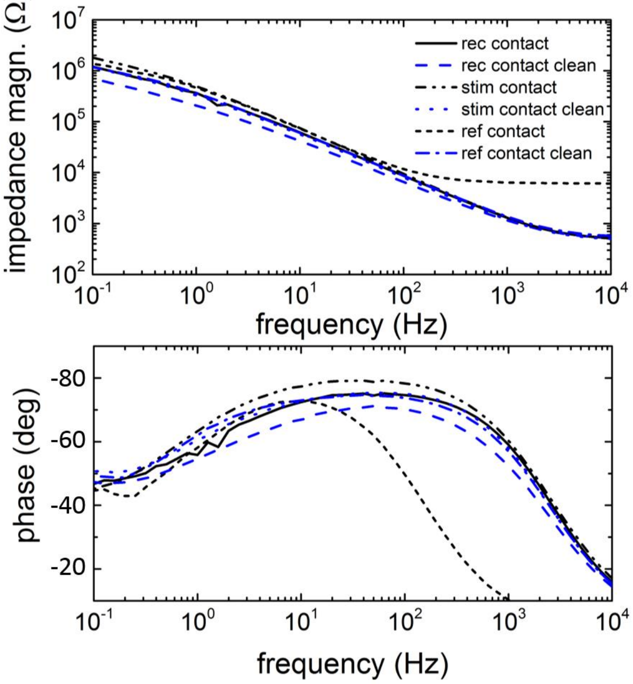

Figure 4: Impedance magnitude and phase of functional contact sites of the explanted electrode array after more than 15 months *in vivo*. Blue lines represent contacts which received trypsin-EDTA treatment prior to EIS measurement.

The access resistance for the mean value over 22 laser-opened PtIr contact sites, each 1.1 mm in diameter, of the unused ECoG electrode was determined to be around 500 Ω, such as the explant's impedance. The cut-off frequency was at 2 kHz. There was no large deviation between the individual contacts (Fig. 5).

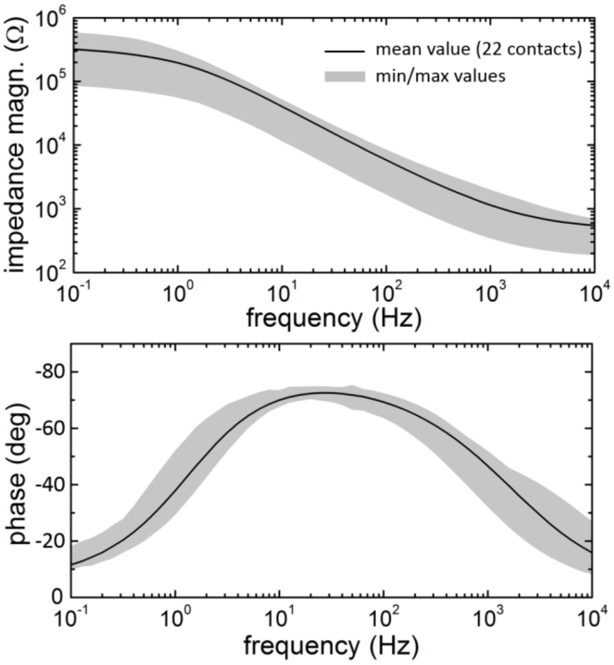

Figure 5: Impedance magnitude and phase of the unused ECoG electrode array. Mean value (black) over 22 PtIr contacts, each with a diameter of 780 µm. The grey band indicates min and max values.

IV. DISCUSSION

Morphological as well as electrical investigations on the explanted electrode array reveal the advantage of the laser-fabrication technology for long-term implanted ECoG electrode arrays. Almost no alterations or signs of upcoming degradation processes were visible after 15 months *in vivo*. Changes in impedance measurements were only present, when any impurities reduced the contact site's active geometrical area (compare reference contacts in Fig. 4). Even right after explantation there was no distinct encapsulation growth on contact sites observable. Only a scattered distribution of organic material which could not be clearly identified as cell residuals. This material was only weakly adherent and could be removed easily. It was not possible to determine any difference between recording or stimulation contacts. EIS measurements and appearance were almost identical, hence no surface modifications or corrosion effects can be assumed. This might be attributable to the very little amount of voltage pulses (pulsewidth 1 ms) which were actually sent over the stimulation contacts ($N < 4000$) during the whole implantation period. Furthermore the amplitudes of the voltage controlled stimulation were sometimes below 1 V and the contacts are comparatively large. In general, no irreversible reactions are assumed for PtIr electrode contacts if the limits of the water window are not exceeded during stimulation. Thus, even with far more pulses passing the phase boundary, no actual material change should be observable. As the lack of chemical adhesion between the electrode's materials, i.e. metal, silicone rubber and parylene C was known beforehand it is important to see, that it did not get worse over 15 months *in vivo*. The whole sandwich assembly, which integrity exclusively relies on mechanical interlocking of the individual layers) definitely appears to be stable over time and hence suitable for long-term utilization. To account for the broken tracks on the ECoG electrode array, design revisions were undertaken for upcoming experiments. Follow-up *in vivo* experiments promise a significantly decreased failure rate so far.

The study presented in this paper was the first out of a series of three animal studies in which the BrainCon implant with this type of ECoG electrode was used. Explantation of the remaining two implants and electrode arrays are expected within the next months after submission of this paper.

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