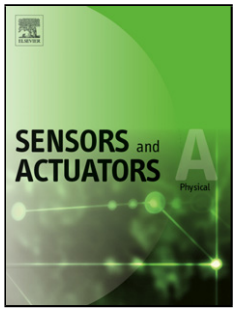

Title: DEVELOPMENT OF A *QUASI-DRY* ELECTRODE FOR EEG RECORDING

Author: <ce:author id="aut0005" biographyid="vt0005">
A.R. Mota<ce:author id="aut0010" biographyid="vt0010">
L. Duarte<ce:author id="aut0015" biographyid="vt0015"> D.
Rodrigues<ce:author id="aut0020" biographyid="vt0020">
A.C. Martins<ce:author id="aut0025" biographyid="vt0025">
A.V. Machado<ce:author id="aut0030"
biographyid="vt0030"> F. Vaz<ce:author id="aut0035"
biographyid="vt0035"> P. Fiedler<ce:author id="aut0040"
biographyid="vt0040"> J. Haueisen<ce:author id="aut0045"
biographyid="vt0045"> J.M. Nóbrega<ce:author
id="aut0050" biographyid="vt0050"> C. Fonseca

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DEVELOPMENT OF A *QUASI-DRY* ELECTRODE FOR EEG RECORDING

A.R. Mota[a], L. Duarte[a], D. Rodrigues[b], A.C. Martins[a,b], A.V. Machado[a], F. Vaz[c], P. Fiedler[d], J. Haueisen[d], J.M. Nóbrega[a], C. Fonseca[b,e *]

[a] Institute for Polymers and Composites/I3N, University of Minho, Campus of Azurém, 4800-058 Guimarães, Portugal

[b] - Universidade do Porto, Faculdade de Engenharia, Departamento de Engenharia Metalúrgica e de Materiais, Rua Roberto Frias, s/n, 4200-465 Porto, Portugal

[c] - Centro de Física, Universidade do Minho, 4710-057 Braga, Portugal

[d] - Institute of Biomedical Engineering and Informatics, Ilmenau University of Technology, Ilmenau, Germany

[e] - SEG-CEMUC – Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

*Corresponding Author, Tel.: +351.22.508.1995, FAX: +351.22.508.1447
e-mail: cfonseca@fe.up.pt (C.Fonseca)

Abstract

The present work reports on the development of a novel polymer-based electrode prototype for electroencephalography (EEG). The new electrode concept lies between the classic “wet” and “dry” electrodes, allowing addressing most of their drawbacks, while keeping the advantages of both. A localized skin hydration effect at the electrode/scalp contact point is achieved by the release of a small amount of a moisturizing agent (30 l) from a reservoir inside the electrode, triggered by the electrode/scalp adduction. The electrode’s functionality relies on the polymer mechanical properties and on the design of an electrode reservoir that deforms upon the application of a specified adduction force. Numerical modeling tools were used for the definition and analysis of the electrode geometry and the material mechanical properties. The new electrode prototype proved to be able to monitor EEG signals similar to those of the commercial silver/silver chloride electrodes by using a fraction of the hydrating solution necessary for the commercial electrodes, thus avoiding to damage or dirtying the patient’s hair. Furthermore, due to the small amount of moisturizing agent employed, the risk of conductive bridges between adjacent electrodes due to gel running is considerably reduced.

KEYWORDS: biopotential electrode; electroencephalogram (EEG); dry electrode; electrocardiogram (ECG); bioelectric signal

1. Introduction

Electroencephalography (EEG) is the recording of the brain electrical activity measured on the scalp surface [1]. EEG is nowadays the most widely used brain imaging technique, as it provides excellent time-resolution of brain activity and offers significant advantages over competing state of the art technologies like MEG (Magnetoencephalography), f-MRI (functional magnetic resonance imaging) and PET (Positron emission tomography) in terms of cost and space requirements. EEG is currently used for epilepsy diagnosis, stroke follow-up, dementia, as well as many other conditions that may affect the brain function. Furthermore, some of the more recent areas of EEG application also include sleep disorder diagnosis, cognitive neurosciences (e.g. brain processes involved in decision-making) and brain computer interfaces. However, despite all the recent technological advances in the acquisition electronics and signal processing, EEG signal recording still remains an important technological challenge, particularly because of the signal transmission at the scalp/electrode interface.

The silver/silver chloride (Ag/AgCl) electrodes have been the main choice of physicians for the recording of EEG signals. The main advantages are their electric potential reproducibility, excellent signal to noise ratio, reliability and biocompatibility [2,3]. Given the increasing spatial resolution of brain activity required by EEG applications, the number of electrodes to use on a single exam may range from 16-32 for clinical settings, to 64 to 256 for research oriented applications. In order to make the electrode preparation faster and more reproducible, several companies commercialize head caps with the electrodes already assembled. However, the preparation of the Ag/AgCl electrodes for an EEG exam still requires several operations, comprising a skin preparation and a local conductive paste application, in order to reduce the electric impedance at the scalp-electrode contact points. It

follows that the preparation process is time consuming and demanding the presence of specialized technical staff. Moreover, gels and adhesive pastes dirty and damage the hair, and may even cause allergic reactions. Short circuits between adjacent electrodes due to accidental gel running are commonly observed, especially when high density electrode setups are used.

A possible alternative to the Ag/AgCl "wet" electrodes are the so-called "dry" electrodes [4-6]. A dry electrode makes use of an inert, conductive material that mechanically couples with the skin for signal transduction, eliminating the use of gel application or skin preparation. Dry electrodes may rely on a dry sensor-skin contact [4-7], or they may work without any physical contact, thus relying on a pure capacitive coupling for signal transfer [8,9]. However, it is noteworthy that, due to the absence of a wet contact, the interfacial impedance is generally in the M range (against a few tens of k for wet electrodes), hence often requiring the integration of pre-amplification within the electrode for proper signal acquisition. As a main advantage of these active electrodes, the pre-amplified signal is much less affected by environmental noise during transmission than with the non-amplified Ag/AgCl electrodes. On the other hand, active electrodes are bulkier, more expensive and more susceptible to movement artifacts, due to the absence of a liquid contact. The disadvantages of dry electrodes have not been overcome so far, in spite of the intense research work performed over the last 50 years and dry electrodes have never reached the commercialization for clinical EEG.

A different approach to EEG monitoring was proposed by Griss and co-workers [10], who developed a dry micro-spiked electrode. The basic idea is to use a micro-needles array to puncture the *stratum corneum* insulating skin layer and thus drastically reduce the interfacial impedance and establishing a stable skin contact. The achieved performance is very close to that obtained with commercial "wet" devices, however part of the spikes were reported to usually break during the

exam and remain embedded in the epidermis. Although a minimally invasive technique, spiked electrodes present an increased risk for infection and inflammatory reactions. Ruffini et al. [11] developed an EEG electrode based in the same principle, but using carbon nanotube technology. Similar drawbacks as for the ones reported for Griss apply to this device.

In order to address the problems of the wet and dry electrodes for EEG, the present work proposes the development of a novel *quasi-dry* EEG electrode that fills the gap between the dry and wet concepts. The new electrode was designed in such a way that:

i) it will pass through the hair, reliably conforming to the scalp;

ii) when a given adduction pressure is applied by the head cap, the electrode releases a microliter amount of a moistener from a built-in reservoir, so the underneath skin layer could be hydrated at the point where the electrode tip touches the scalp.

The electrode geometry and mechanical requirements were defined through the aid of numerical modelling tools. The electrode prototype was produced by mould casting of a polyurethane thermoset and a silver coating was applied by electroless plating, in order to provide the necessary conductive and sensing properties to the electrode.

2. Materials and Methods

2.1. Electrode design and fabrication

The electrode geometry and mechanical properties of the material to be employed were defined with the aid of a numerical modelling (Solidworks Simulation®, Dassault Systèmes, France). For that purpose, several concepts were tested in order to obtain a geometry that expelled the

defined amount of the hydrating solution off the reservoir upon the application of the typical coupling force. Subsequently the main mechanical properties of the material, namely its elastic modulus, were identified. A typical value of such coupling force was measured by using a Nihon Kohden cap (NIHON KOHDEN EUROPE GmbH, Rosbach, Germany) and a wet bridge electrode.

The polyurethane (PU) electrode body was produced by using a mixture of a diisocyanate and a diol, a two component thermoset PU (DIPRANE* 5278 Prepolymer and Phoenix Polyester blended Polyol, BMP Europe Ltd). The mixture was prepared using a percentage of 48% polyol and 52% prepolymer, at 45 C. Afterwards, the mixture was casted into a mould kept at 100 C. The filled mould was then placed in a vacuum heater during 20 min (100 C and -1 bar), to promote the required PU curing. A scheme of the mould is reported in Fig. 1. A cross-section and a general overview of the assembled mould are shown in Figures 1(ii) and 1(iii), respectively. When assembled, the parts “d1”, ”d2”, “e1”, “e2” and “f” form the mould cavity, that should be filled with the raw material used to produce the electrode. Prior to mould filling, the material is placed in the cavity of the hopper “c”, and is subsequently forced to the mould cavity by the action of piston “b”. The plate “a” is used to apply the load required to force the mould cavity filling.

2.2. Electroless silver plating and silver chloride formation on the electrodes

The PU electrodes were first ultrasonically cleaned in isopropanol (10 minutes) and distilled water (10 minutes). The electroless plating of the samples took place in two steps: (i) a silver pre-deposition treatment, aimed at creating silver seeds at the surface to improve the surface affinity for silver and (ii) silver film growing through a Tollens like plating process. The procedure was adapted from references [12-14]. The parts were first soaked in a 3.5M silver nitrate solution (Normapur,

99.8%) for one hour, followed by the immersion of the silver nitrate swollen samples (about 5% swelling) in a 70mM sodium borohydride (Sigma-Aldrich, >98%) reduction solution for 10 minutes, with strong stirring. Finally, the samples were dipped in the Tollens plating solution. This solution was prepared by adding drop wise concentrated ammonia (ACS, Sigma Aldrich, 28-30% NH_3) to a 0.1M silver nitrate solution, until a transparent solution was obtained. From that point, an excess of 8 mL of ammonia /L solution was added. Then, tri-sodium citrate tri-hydrate (ACS, Sigma Aldrich >99%) was added to the final solution to reach a 2% (m/v) concentration. Finally, a 24% (m/v) solution of glucose (ACS, Sigma Aldrich) was prepared and added to the silver solution, where the PU samples were already immersed (silver to glucose volume ratio is 2:1). The reaction mixture was tightly closed, and let at room temperature for 16 hours, to achieve a silver thickness of about 2 m. The coated samples were finally washed with distilled water and dried at 65 C until constant weight.

The formation of the AgCl layer was achieved under the application of a constant anodic current of 10 mA/cm^2 for 30 s to the silver-coated PU samples [15]. A EG&G PAR 273A potentiostat (Princeton Appl. Res. US) driven by Corrware® software (Scribner Associates Inc., US) was used for the galvanostatic treatments.

2.3. Silver coatings analysis

The morphology of the samples was probed by scanning electron microscopy (SEM), carried out with a Jeol JSM 6301F microscope, operating at 15 keV. The open circuit potential was acquired with a 1 S/s sampling rate, using the hardware/software mentioned before. The impedance spectroscopy analysis was carried out with the EG&G 273A potentiostat coupled to a Solartron 1250 frequency response analyser (Amtek Inc., UK) and driven by the ZPlot® software (Scribner Associates

Inc., US) by using a 7 mV (rms) AC signal. The adhesion of the silver coating to the PU was assessed by the empirical X-cut tape test, performed according with ASTM D3359-08. A grid was drawn on the sample surface with a sharp knife, after which a strong tape was firmly applied to the sample and rapidly removed.

2.4. EEG testing protocol and signal evaluation

For signal acquisition, amplification and recording four unipolar inputs of a commercial biosignal amplifier (Refa amplifier, Advanded Neuro Technology B.V., Enschede, Netherlands) were used at a sampling rate of 1024 S/s. Recording and online processing was performed using ASA© software (ANT B.V., Enschede, Netherlands). A second amplifier of the same type was used in combination with conventional Ag/AgCl bridge electrodes for simultaneous acquisition of reference EEG signals. The *quasi-dry* electrode was fixed to the support of a commercial bridge electrode, through an adaptation accessory, and fixed just like a normal bridge electrode with the Nihon Kohden cap, see Fig.2. A scheme of the measurements setup is shown in Fig.3. For contacting electrode and signal acquisition unshielded copper cables were used, which were soldered to special brass electrode mountings. Inductive coupling and differential noise picking among cables was minimized by binding the cables together.

A conventional Ag/AgCl electrode and a *quasi-dry* electrode were positioned right beneath each other (distance of 2 cm) at Fp1, Fp2, O1 and O2 positions according to the international 10-20 system of electrode placement [1]. The electrodes were applied in combination with electrolyte gel (Electro-Gel, Electrocap International Inc., USA) and fixated with a Nihon Kohden silicone cap.

An additional patient ground electrode (self-adhesive ARBO Ag/AgCl electrode) was placed at Fpz position and connected to the patient ground inputs of both amplifiers.

The tests were performed with one volunteer, aged 46 years, with normal skin and hair condition (about 2 cm long). Besides preliminary cleaning of the skin using ethanol, no additional preparation was performed. A reference test using two sets of Ag/AgCl electrodes provided data for objective signal quality evaluation and for the estimation of the influence of the different set positions. During the whole test sequence different episodes of data were recorded:

- spontaneous resting EEG,
- EEG with eye blinking as well as eye movement and eye open/close artifacts,
- EEG with alpha activity with eyes closed,

Signal evaluation was carried out in MATLAB (The Matworks Inc., USA). All recorded signals were filtered using a Butterworth band pass with cut-off frequencies at 1 Hz and 200 Hz as well as a bandstop for 50 Hz (45-55 Hz). Subsequently, characteristic parameters like Root Mean Square Deviation (RMSD) and Sperman's rank correlation were calculated according to Equation 1 and 2, respectively:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n} (w_i - d_i)^2}{n}} \quad (1)$$

$$CORRELATION = \frac{\sum_i \left(w_i - \overline{w}\right)\left(d_i - \overline{d}\right)}{\sqrt{\sum_i \left(w_i - \overline{w}\right)^2 \sum_i \left(d_i - \overline{d}\right)^2}} \quad (2)$$

where w_i and d_i correspond to the i^{th} data sample acquired with the reference (Ag/AgCl) and test electrodes (*quasi-dry* or Ag/AgCl), respectively. Furthermore, the Welch estimation of the power spectral density (PSD) was calculated. Prior to visual inspection of the signals at O1 position in time domain (cp. Fig. 10) a single Butterworth band pass filter with cut off-frequencies at 1 Hz and 40 Hz was applied.

3. Electrode Concept Development

The *quasi-dry* electrode concept aims at putting together the advantages of the "wet" and "dry" electrode concepts. As such, the following specifications were taken into account during the design procedure:

- the scalp surface should be locally hydrated with a small amount of a solution to avoid dirtying or damaging the hair and gel running among electrodes. Yet, the moisturizer volume should be enough to locally hydrate the scalp, decreasing the electrode/scalp impedance and efficiently coupling the electrode to the scalp. One aimed at a hydrating solution volume of about 30 µl (volume of a small drop), which is considerably less than the 1-2 ml of gel that is traditionally used;

- the solution should be kept in a reservoir, connected to the electrode, and be expelled upon the application of a small adduction pressure, e.g. the pressure exerted by the Nihon Kohden cap against the electrode/scalp contact;

- a conductive coating should be applied to the electrode's body, so that the signal could be transmitted from the scalp surface to the recording apparatus. Besides being electrically conductive, the coating should be i) biocompatible, ii) chemically inert and able to produce a low noise contact

with the scalp, iv) capable of withstanding deformation without losing the conductivity and, v) mechanically resistant to repeated manipulation and cleaning.

- finally, the electrode dimensions should be such that it could fit the plastic support of a commercial bridge electrode.

A concept drawing of the proposed device is depicted in Fig.4. The electrode reservoir may be filled with a syringe and the diameter of the orifice should be large enough to let the liquid be expelled with the application of the adduction pressure but not so large that it can't avoid fluid leakage at rest. The diameter is mainly correlated with the viscosity of the moistener.

4. Results and Discussion

4.1. *Electrode Design and Fabrication*

A value of circa 3 N was obtained as the average force necessary to decouple a bridge electrode fixed to the scalp with a Nihon Kohden cap. According to the electrode specifications, defined in Section 3, this should be the force exerted to expel the moistener fluid. Additionally, to minimize the risk of the coating failure when in-service, the electrode deformation should be minimized. According with these requirements it was possible to set both the electrode geometry and the required material mechanical properties, to be employed on the electrodes production. Several geometries were simulated numerically, subsequently selecting the design that allowed expelling the required moistener amount with the least possible surface deformation. The behavior of the selected geometry is shown in Fig. 5. As illustrated, a reduction of the moistener reservoir volume is achieved

upon the application of a 3N vertical force when the elastic modulus for the polymer is around 4-6 MPa (symmetry around the vertical electrode axis should be considered). The diameter of the orifice (3 mm) was defined according with the diameter of similar orifices existing in common pipettes, which proved to be appropriate for the used moistener fluid. The final electrode without and with the silver/silver chloride coating is shown in Figs. 6a and b respectively.

4.2. Coating characterization

Silver was chosen as the coating metal for two main reasons: first, it is the best metal for electrophysiological sensing applications, especially when combined with a AgCl outer layer, as stated before; secondly, silver displays a strong chemical affinity for the amide groups on PU, thus ensuring a good coating adhesion.

Electroplated silver coatings revealed a rough structure, with a closely packed granular morphology, as shown in Fig.7. A film thickness of around 2 m was estimated from weight measurements and confirmed from cross-section SEM analysis (results not shown). The resistivity of the coating, as measured with the four point technique, is 15 ·cm. This is about one order of magnitude above the resistivity of pure silver, which may be caused by the incorporation of impurities from the electroplating solution, namely the citrate inhibitor that adsorbs on silver [15]. However, the observed resistivity is still metallic-like and perfectly suitable for the envisaged application. Furthermore, the total resistance of the electrode proved to remain stable upon deformation, another important requirement for the envisaged application. The adhesion tests showed no evidence of any delamination, particularly at the cut interceptions, not even after repeating the test several times.

The recording of the electrochemical potential vs. time for a couple of Ag/AgCl coated PU samples in an isotonic sodium chloride solution is reported in Fig.8. A sub-mV difference between electrodes attests the good potential reproducibility, achieved after the silver chloridization treatment. In fact, a top silver chloride layer has proved essential for a silver electrode to display a stable electrochemical potential [2,3]. On the other hand, the maximum drift rate is about 4 V/s after connecting the electrodes, but it rapidly falls below 1 V/s. These results are in line with the results of Talgreen [3] and Huigen [16] for commercial Ag/AgCl electrodes, attesting the suitability of the PU coated samples for EEG application from the electrochemical potential stability point of view. The observed drift should be related with small differences between the coatings, namely porosity or chemical composition. A low electrode potential drift proved to be particularly important when low frequency EEG is being recorded.

The impedance at the electrode/moistener interface is also a relevant parameter to obtain a reliable signal transfer, as the lower the interfacial impedance the more immune the signal will be to noise and movement artifacts and electromagnetic interference [4]. The impedance vs. frequency study showed that impedance values lay bellow 60 $\cdot cm^2$ at 100 mHz, not far from bulk silver/silver chloride electrodes [17], as shown in Fig.9. Such low impedance values relate with the fast kinetics of charge transfer at the electrode surface, given by the equation:

$$Ag^+ + Cl^- \rightleftharpoons AgCl + \text{electron} \qquad (3)$$

and also to the strong roughening of the silver surface that accompanies the formation of the AgCl layer.

4.3. In- vivo testing of the electrodes

The *quasi-dry* electrodes reliably allowed for EEG signal acquisition during the approx. 30 minutes of *in-vivo* testing by using the described Nihon Kohden cap system. Overlay plots of characteristic signal episodes containing resting EEG at the O1 position are shown in Fig.10, in time domain. The signals closely resemble each other. Although the shown signal episodes are only 4s in length, the observation for longer periods produced similar results. After manual extraction of artifact-afflicted episodes and signal processing according to the description in 2.4, the power spectral density, RMSD and correlation values were calculated. Fig.11 shows the Welch power spectral density estimation of channel O1 for a signal episode of 30 sec containing resting EEG. The average power according to the PSD spectra in figure 11 are 4.1 V_{RMS} for both kinds of electrodes. Thus, as for the time domain, the frequency domain proves similar signal characteristics for both compared types of electrodes.

The calculated RMSD and correlation values for eye blinking and spontaneous EEG are listed in Table 1. The results represent the mean values over all four channels namely Fp1, Fp2, O1, and O2. It is clearly visible that the RMSD and correlation values are in the same order of magnitude in the Ag/AgCl vs. *quasi-dry* electrode tests and in the Ag/AgCl vs. Ag/AgCl reference tests. Furthermore, the STDs of the RMSD values are close to or even below the actual difference between both test setups. Thus, most of the signal differences must be associated to small distance differences between the compared electrodes as well as external noise. Anyway, the correlation values for the Ag/AgCl reference tests are always higher than the corresponding values of the *quasi-dry* tests, meaning that with the Ag/AgCl electrode couple the resulting signals more closely resemble each other. This might

result from a slightly decreased spatial distance between the compared electrodes in the Ag/AgCl reference test.

In spite of the good performance of the new electrode, some technical problems related with the electrode placement were noticed. For example, after the initial application, it was sometimes necessary to provide additional pressure for the electrodes to dispense the gel, a problem related with the non-uniform pressure provided by the Nihon Kohden fixation system on one hand, and some adaptation problems of the new electrode to the bridge electrode support on the other hand. These problems would be readily addressed with the development/adaptation of a cap that takes into account the specificities of the quasi-dry electrode. Furthermore, a longer, tube-like electrode tip would facilitate the electrode/scalp contact, what will be implemented in the next generation of the *quasi-dry* electrodes. Moreover, a new cap/electrode fixation system will consider the possibility of expelling the gel with a finger's pressure instead of the cap pressure, thus avoiding any unexpected or premature moistener release.

5. Conclusions

A novel electrode concept for EEG recording, aiming at addressing the problems of the currently proposed electrodes, has been developed and an electrode prototype was fabricated and tested *in-vivo*. The electrode is able to expel a 30 l amount of a hydrating agent, thus substantially reducing the volume of gel that is commonly used and restricting it to the electrode/contact point. Thermoset PU coated with an Ag/AgCl chemically deposited layer was chosen to prototype the electrode concept.

The *in-vivo* tests showed that the *quasi-dry* electrode was able to reliably acquire EEG signals similar to those of the commercial Ag/AgCl reference electrodes, validating the new concept for biopotential monitoring. The *in-vivo* experiments also showed that for the new electrode to achieve its full potential it must be combined with a dedicated cap, able to reliably apply a constant pressure to every electrode. Finally, the new concept may be easily adapted to the monitoring of other biopotential signals (EMG, ECG).

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Biographies:

Armando Mota was born in 1988 in Portugal. He obtained a M.Sc. in Polymer Engineering at the University of Minho in 2011. Since then he has been working as a researcher in the Institute for Polymers and Composites, a research unit form the University of Minho, in a project that aims the characterisation of the cooling stage in profile extrusion. He is author of 4 presentations in international conferences and 2 submitted patents.

Luís Duarte was born in 1987 in Portugal and obtained a M.Sc. in Polymer Engineering in 2010. During the graduation he worked with a multidisciplinary team in a project aiming the development of entrepreneurship skills. He is currently working as Plastic Injection Engineer and he is responsible for the production planning.

Diogo Rodrigues received the M.Sc. degree in Bioengineering from University of Porto (Portugal) in 2012. During his studies he was immersed in a wide range of bioengineering scientific areas such as biomaterials, tissue engineering, nanotechnology and electrophysiology and was also involved in some projects in this field. Recently, his research interests include the biomaterials science for tissue engineering, drug delivery systems, biosensors and medical devices.

A. Martins was born in Vila Nova de Famalicão, on the year of 1989. She obtained the MSc degree in Biomedical Engineering at the University of Coimbra in the year of 2012. Her diploma thesis was related with the development of a new non-invasive biosensor for EEG signal acquisition, with potential use in newborns. Since September 2012 she has been working as a researcher at the University of Minho (Guimarães, Portugal) in bioelectrode development, in a project supported by the Portuguese Foundation for Science and Technology (FCT).

Ana Vera Machado is an Assistant Professor at the Polymer Engineering Department of the University of Minho in Portugal. She received a Ph.D. from the University of Minho, in Polymer Science and Engineering in 2000. The main scientific research areas are polymers blends, copolymerization, polymer modification and nanocomposites. She published over 90 papers in peer reviewed international journals or book chapters and presented more than 150 communications in international conferences. Since 2010, she is the Director of the Institute for Polymers and Composites (R&D Institution) and Director of I3N (Associated Laboratory in the area of nanomaterials and nanotechnology).

Filipe Vaz graduated in Physics and Chemistry at the University of Minho, Portugal in 1992, where he obtained also his PhD degree in Physics in 2000. Main research topics concern hard nanostructured thin films, with targeted applications varying from tools and machine parts, including polymers. From 2001 he is also developing new optical thin film systems, based on oxynitrides, oxycarbides, and their mixing. Recently, his research is focused on the physics and technology of magnetron sputtered thin films containing noble metal nanoparticles, namely gold and silver, revealing Surface Plasmon Resonance behaviour.

Patrique Fiedler was born in 1984 in Germany. He obtained a M.Sc. degree in electrical engineering at the Ilmenau University of Technology (Germany) in 2009. Thereafter, he joined the Institute of Biomedical Engineering and Informatics at the Ilmenau University of Technology as a Ph.D. student under the supervision of Prof. Jens Haueisen. His research interests include the development of novel dry electrodes for biosignal acquisition with focus on polymer and textile based electrodes for electroencephalography and electrocardiography.

Jens Haueisen received a M.S. and a Ph.D. in electrical engineering from the Technical University Ilmenau, Germany, in 1992 and 1996, respectively. From 1996 to 1998 he worked as a Post-Doc and from 1998 to 2005 as the head of the Biomagnetic Center, Friedrich-Schiller-University, Jena, Germany. Since 2005 he is Professor of Biomedical Engineering and directs the Institute of Biomedical Engineering and Informatics at the Technical University Ilmenau, Germany. His research interests are in the numerical computation of bioelectric and biomagnetic fields and biological signal analysis.

J. Miguel Nóbrega is an Assistant Professor at the Polymer Engineering Department of the University of Minho. His research lies on three overlapping areas: product design, polymer processing and rheology. He was/is involved in the supervision/co-supervision of 24 MSc thesis and 8 PhD thesis. He is author/co-author of 10 book chapters, 32 papers published in international refereed journals, 7 patents (4 international), 110 communications presented in international conferences (12 invited) and 12 communications presented in national conferences. He is co-editor and co-author of the book entitled “Design of extrusion forming tools”, that was published by Smithers Rapra on December 2012.

Carlos Fonseca received his PhD degree in Electrochemistry in 1997. He is an Assistant Professor of Materials Science and Biomedical Engineering at the Faculty of Engineering of the University of Porto and a Researcher of the Mechanical Engineering Centre, Coimbra University (CEMUC). His current research interests are focused in the areas of biomedical devices, namely bioelectrode development, biomaterials and thin film metal coating of polymer materials.

FIGURE CAPTIONS

Figure 1 –Mould manufactured for the production of PU electrodes, composed by: “a” plate, “b” piston, “c” hopper, “d1” and “d2” mould cavity, “e1” and “e2” piston support and “f” piston **(a)** exploded view, **(b)** assembled section view and **(c)** assembled general overview (dimensions in mm).

Figure 2 – photo showing the *quasy-dry* electrode fixation system, which was adapted from the commercial silver bridge electrode. The inner part of the adaptation accessory has a metallic part, where the electrode is fixed.

Figure 3 - Recording scheme for the bipolar EEG tests. The filled circles represent the *quasi-dry electrodes* and the non-filled circles represent the Ag/AgCl electrodes.

Figure 4 – Scheme of the *quasi-dry* electrode concept, according with the requirements listed in the text. In dark is represented the volume of the reservoir.

Figure 5 – Deformation of the electrode body upon the adduction force applied by the cap (3N). Due to symmetry conditions just a small axisymmetric region of the electrode was considered for modeling purposes.

Figure 6 – manufactured polyurethane electrode before **(a)** and after silver coating **(b)**

Figure 7 – surface morphology of the PU silver/silver chloride plated samples with two different magnifications

Figure 8 – Open circuit potential of two Ag/AgCl-coated PU samples immersed in an isotonic NaCl solution. The inset shows the electrochemical potential drift rate at several instants.

Figure 9 – Bode spectrum for an Ag/AgCl-coated PU sample in contact with an isotonic NaCl solution.

Figure 10 - 4 seconds of resting EEG signal for reference Ag/AgCl and *quasi-dry* electrodes at the O1 position, in time domain.

Figure 11 – PSD for 30 seconds of resting EEG signal for reference Ag/AgCl and *quasi-dry* electrodes at the O1 position.

TABLE CAPTIONS

Table 1: RMSD and correlation results for the *quasi-dry* and the reference spontaneous EEG tests. Values represent mean over all four channels (Fp1, Fp2, O1 and O2).

	Ag/AgCl vs. Quasi-dry			Ag/AgCl vs. Ag/AgCl		
Test	RMSD (μV)	STD of RMSD (μV)	Correlation	RMSD (μV)	STD of RMSD (μV)	Correlation
Resting state EEG	5,75	1,34	0,61	6,33	0,79	0,65
Alpha activity EEG	5,65	1,37	0,62	4,16	0,58	0,69
Eye open / close test	8,33	2,17	0,71	9,24	2,65	0,77
Eye blink test	6,42	1,26	0,94	4,22	0,79	0,97

HIGHLIGHTS:

- a new EEG bioelectrode lying between the wet and dry electrode concepts was developed

- the electrode expels 30 l of moistener upon the application of the adduction pressure

- electrode design and polymer properties were optimized by finite element analysis

- *in-vivo* EEG testing demonstrated a performance similar to commercial electrodes

FIGURE 1

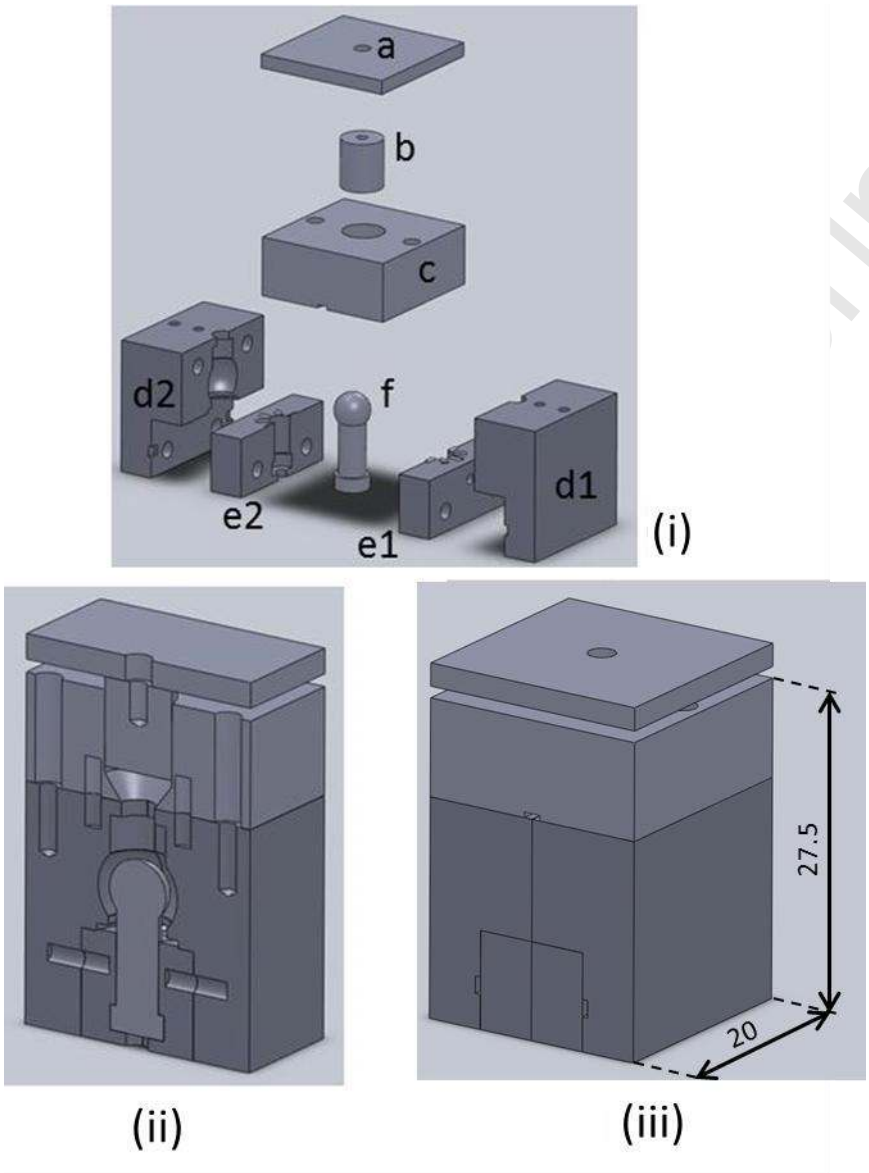


FIGURE 2

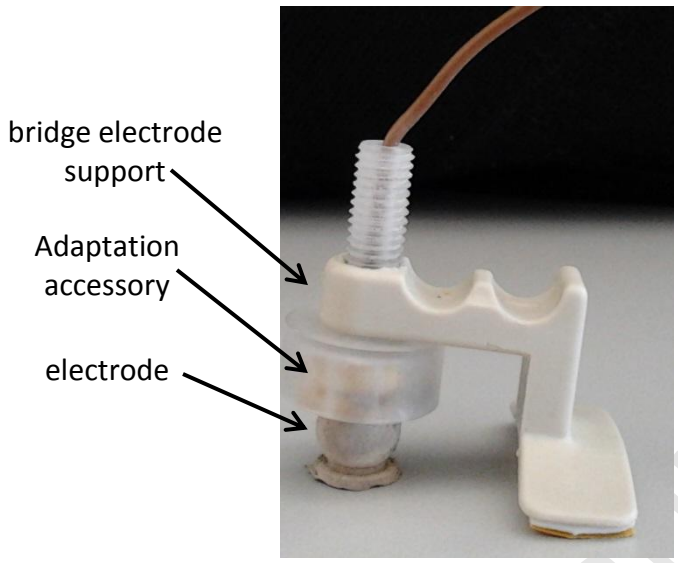


FIGURE 3

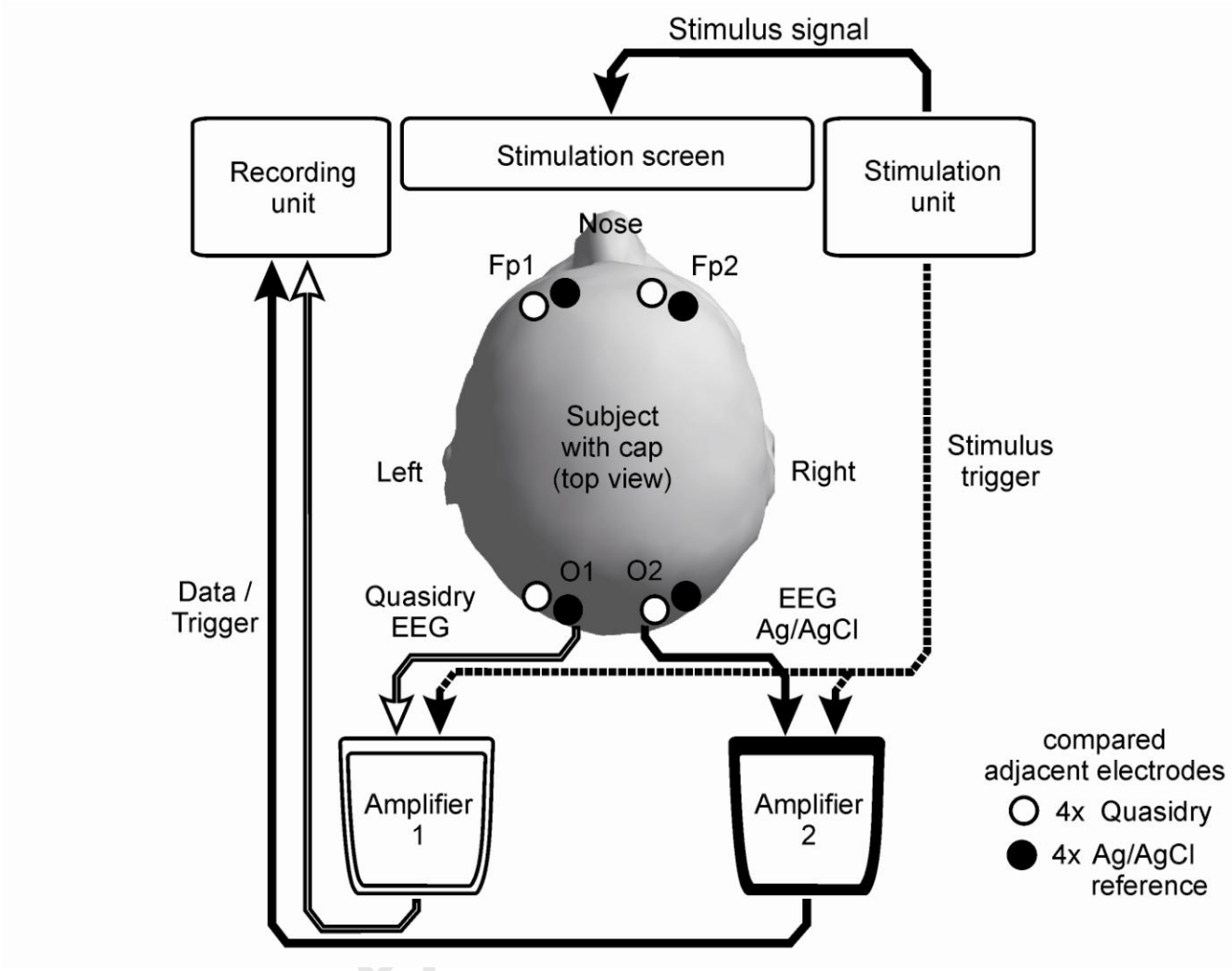


FIGURE 4

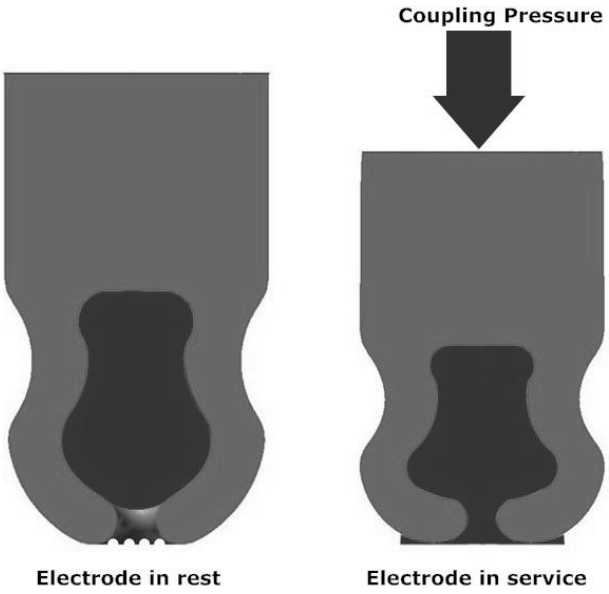
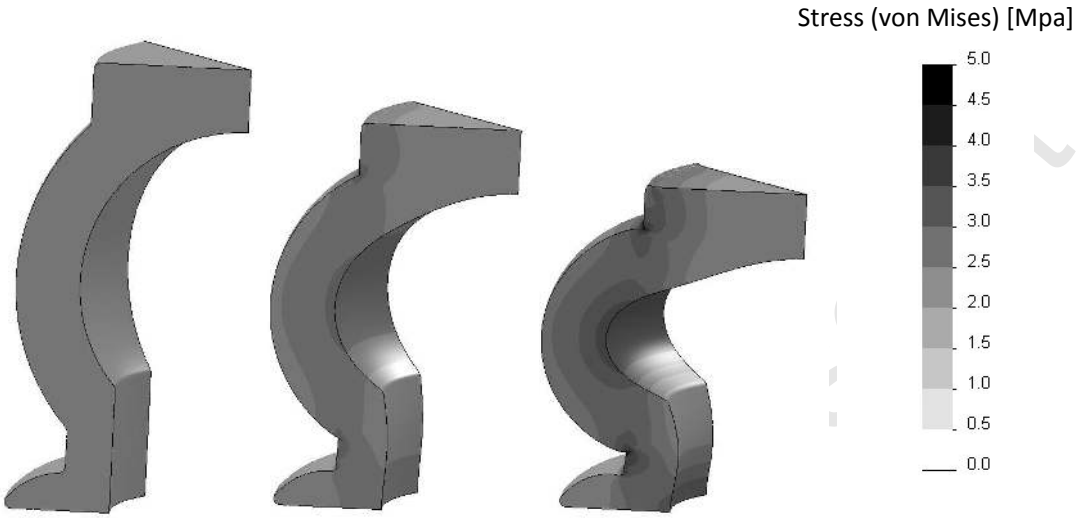


FIGURE 5



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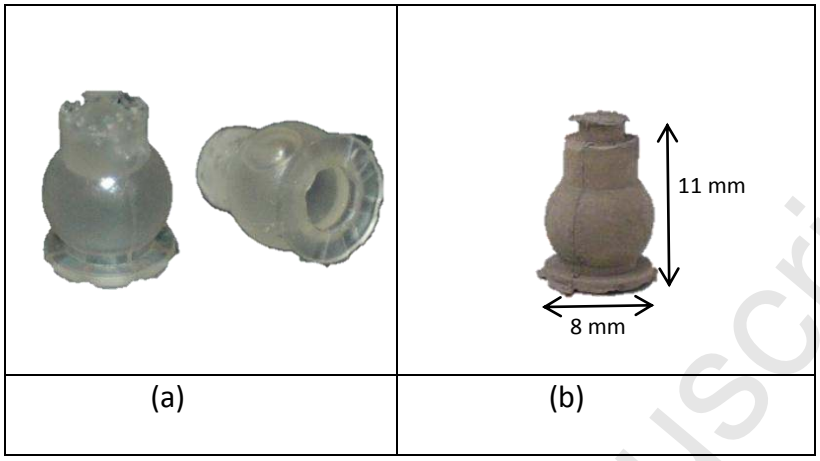
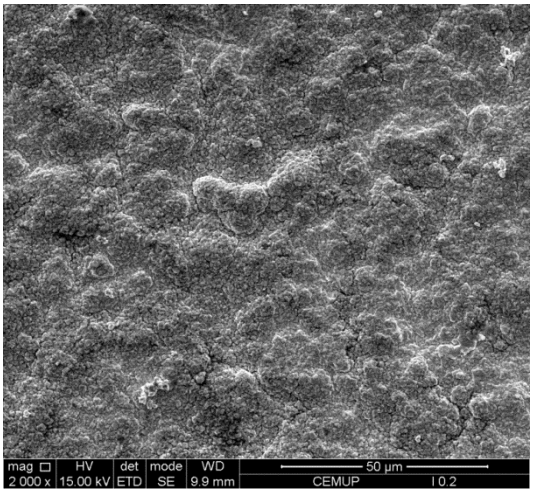


(a) (b)

FIGURE 7



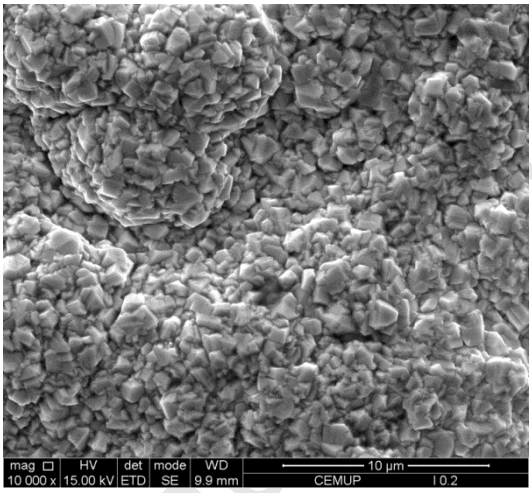


FIGURE 8

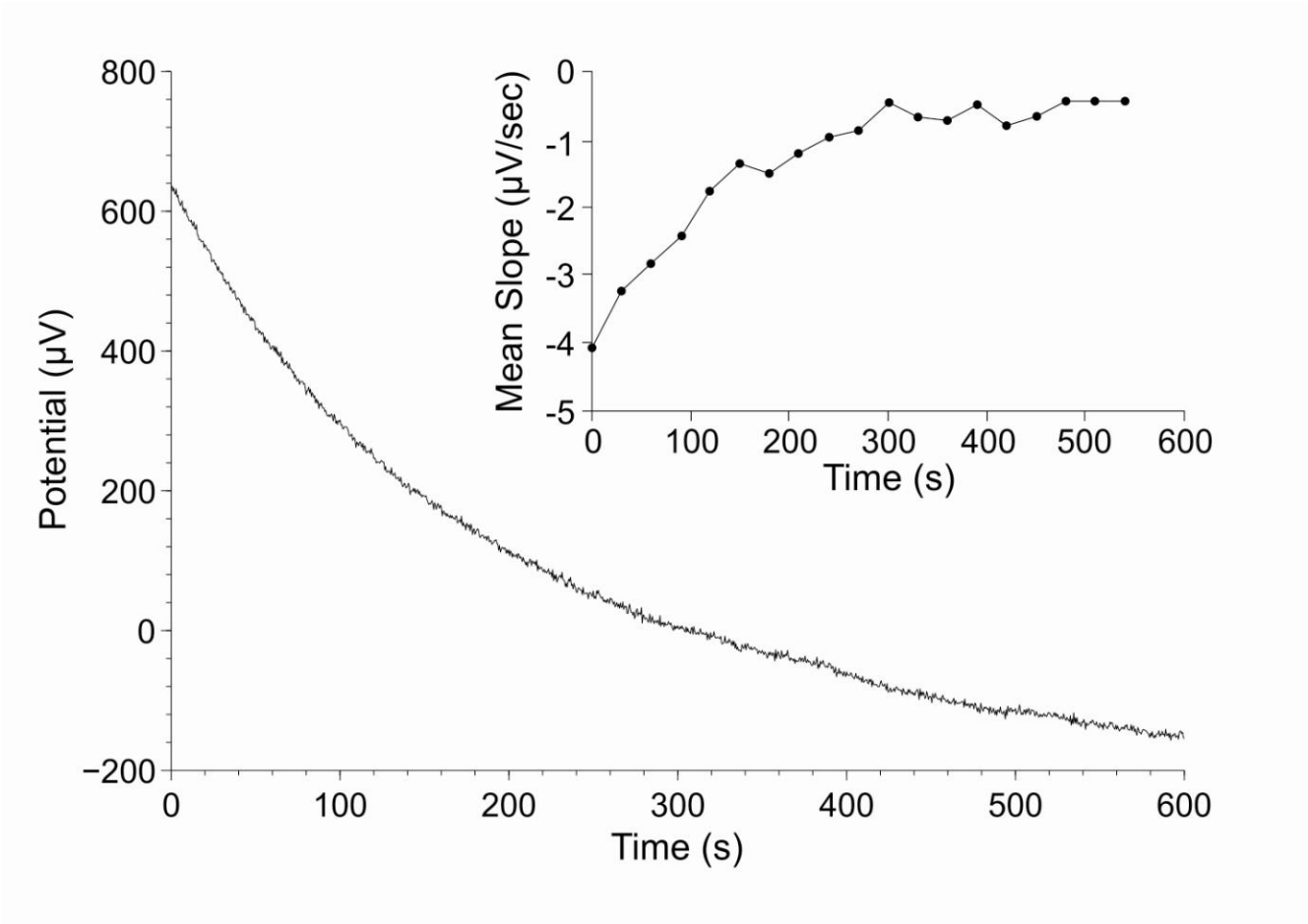


FIGURE 9

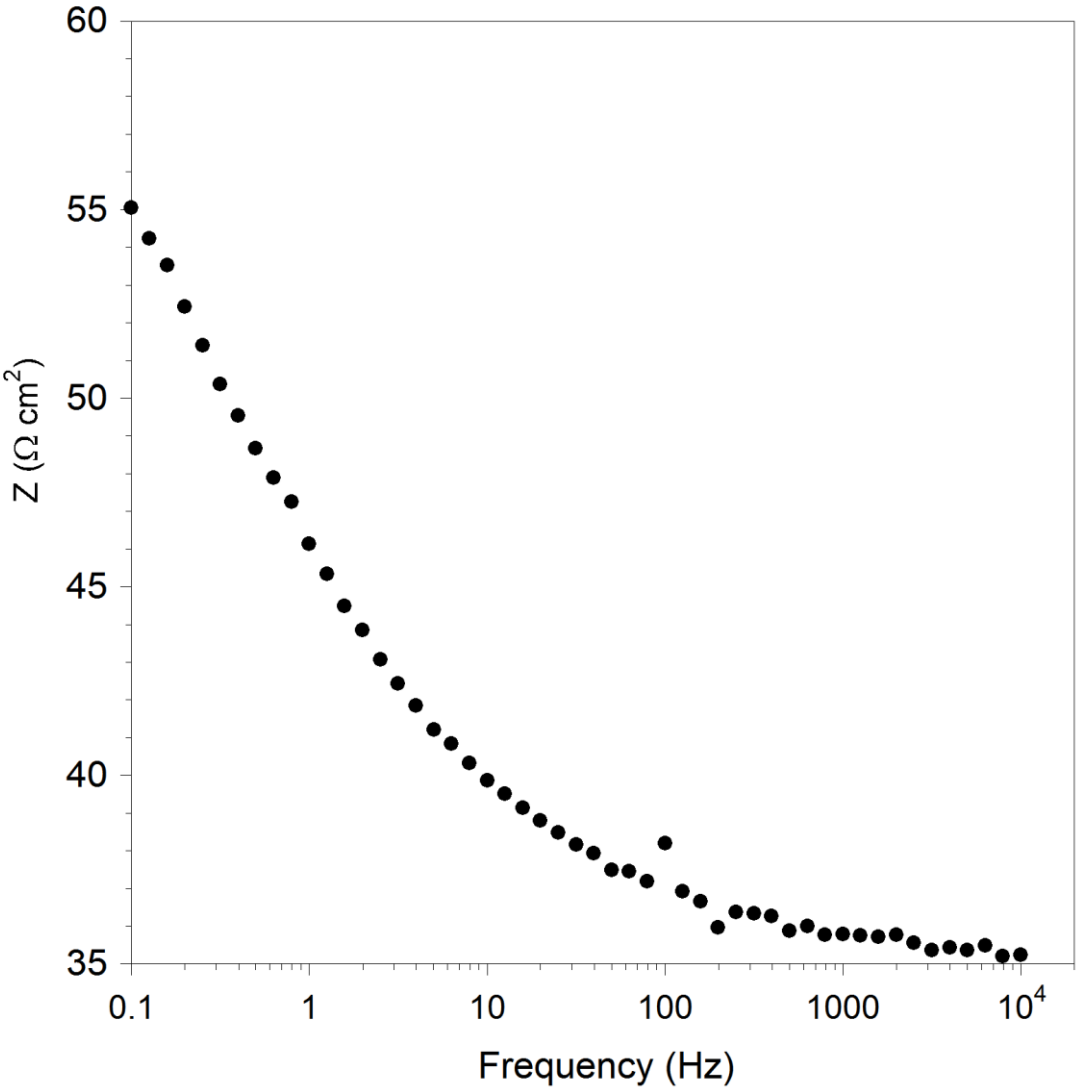


FIGURE 10

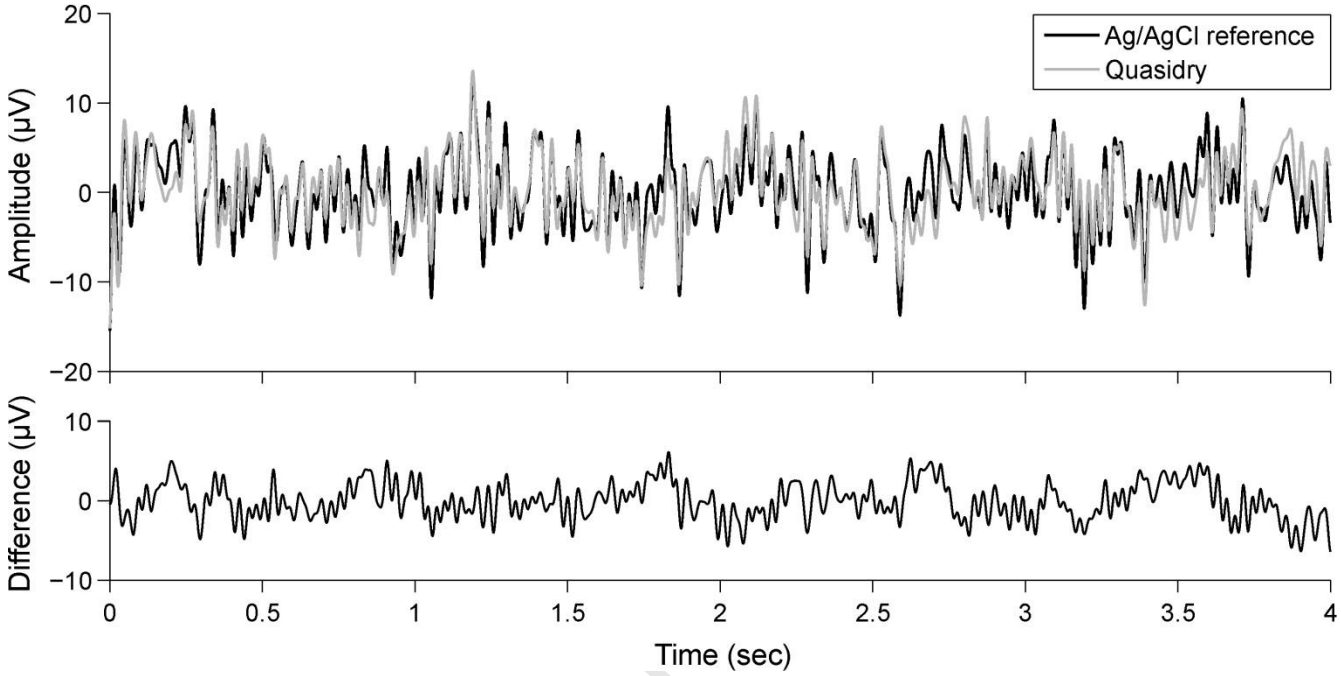


FIGURE 11