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Novel Flexible Dry Multipin Electrodes for EEG: Signal Quality and Interfacial Impedance of Ti and TiN Coatings*

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***Abstract*— Conventional Silver/Silver-Chloride electrodes are inappropriate for routine high-density EEG and emerging new fields of application like brain computer interfaces. A novel multipin electrode design is proposed. It enables rapid and easy application while maintaining signal quality and patient comfort. The electrode design is described and impedance and EEG tests are performed with Titanium and Titanium Nitride coated electrodes. The results are compared to conventional reference electrodes in a multi-volunteer study. The calculated signal parameters prove the multipin electrode concept to reproducibly acquire EEG signal quality comparable to Ag/AgCl electrodes. The promising results encourage further investigation and can provide a technological base for future preparation-free multichannel EEG systems.**

I. INTRODUCTION

The quality of biosignals is relying on stable intrinsic and interfacial electrochemical characteristics of the applied biomedical sensors. Silver/Silver-Chloride (Ag/AgCl) electrodes have been the preferred type of electrode for biosignal acquisition since several decades. They provide exceptionally reliable electrochemical characteristics including a stable open circuit potential, low noise level as well as low and stable electrode-skin interfacial impedance. However, conventional Ag/AgCl electrodes require careful, time-consuming individual point-of-contact preparation and application of additive electrolyte materials.

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Considerable inherent drawbacks emerge from these requirements, in particular for multichannel electroencephalography (EEG). The preparation procedure delays signal acquisition, increases patient stress and cost of operation. The electrolyte additives limit long-term investigations and cause risks of falsified measurements due to inadequate preparation, conductive bridges between electrodes as well as skin irritation or allergic reactions [1],[2]. Conventional Ag/AgCl electrodes are thus inappropriate for emerging new fields of application for EEG including continuous and mobile monitoring, ambient assisted living, and brain-computer interfaces.

Alternative dry sensor concepts aim to avoid preparation and additive-specific problems by enabling dry-contact or even non-contact signal acquisition, thus dramatically simplifying application. Non-contact approaches include fully capacitive [3],[4] as well as opto-electric sensors [5]. They require extensive electronics and are highly susceptible to relative movements. On the other hand dry-contact concepts include electrodes with specific pin-type [6], spiked [7], foam [8] or bristle [9] shapes, doped or subsequently coated with electrically conductive materials. None of these electrodes are currently used in routine applications, as they are either too expensive, require special electronics and equipment or involve, again, too complex preparation.

Our research is focused on developing a dry-contact electrode technology enabling simplified, mobile multichannel EEG acquisition while avoiding the need for preparation or special electronics. Thus, we developed a specific, flexible substrate shape which we call multipin (MP) electrode. The specific shape is capable of interfusing the hair layer and enabling stable contact with the scalp. In a preliminary test on a single volunteer a titanium nitride (TiN) coated MP electrode proved to provide Ag/AgCl-comparable signal quality [10]. In the current paper a further comparison of two different titanium (Ti) and TiN coated MP electrodes as well as a conventional Ag/AgCl reference electrode is performed in terms of electrode-skin interfacial impedance and EEG signal quality in of a multi-volunteer study.

II. MATERIALS AND METHODS

A. Multipin Ti and TiN electrodes

The shape of a dry-contact electrode must enable hair layer interfusion and provide sufficient contact surface, reliability and stability as well as patient comfort. The developed MP electrode substrate is based on thermoset polyurethane (Biresin U1419, Sika, Germany) that comprises these requirements by combining the contact surface of multiple thin pins on a single common baseplate. The polyurethane (PU) enables specific, selectable flexibility ensuring adjustability and patient comfort. Variable pin-shortcuts due to extensive bending can be avoided, while maintaining comfort and adaptability to local head curvature.

Ti and TiN are well known for their biocompatibility and electrochemical characteristics due to a wide range of medical applications. Furthermore, our recent studies also proved sufficient signal quality in EEG [11] as well as electrochemical stability in contact with human sweat [12]. Thus, these materials have been selected for the electrically conductive coating of the MP electrodes. After cleaning of the uncoated PU substrates, thin films of Ti or TiN were deposited during a multi-phase sputtering process, using a reactive DC magnetron sputtering technique in a laboratory-sized deposition system. The multi-phase sputtering process produces well adherent, dense and homogeneous thin-film coatings (thickness < 600 µm) on the substrates.

The design of the tested MP electrodes is shown in Fig. 1 along with an uncoated substrate and a TiN-coated electrode.

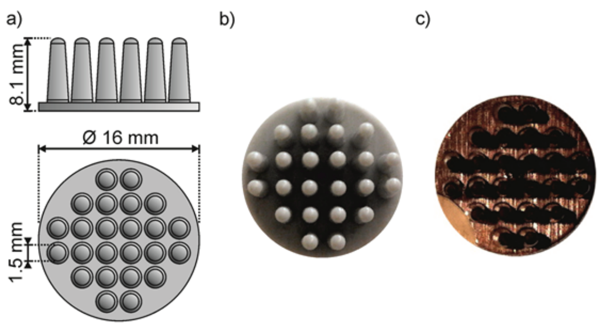

Figure 1. Electrode shape comprising 24 pins on one baseplate: a) basic design, b) uncoated polyurethane substrate, and c) coated electrode (TiN).

B. In-vivo electrode-skin interfacial impedance tests

The in-vivo tests were performed for TiN and Ti coated MP electrodes as well as a conventional Ag/AgCl ring electrode for an overall number of eight volunteers. All volunteers had healthy skin conditions and normal nutrition. All EEG test volunteers were male while for the impedance tests four volunteers were male and four female. In each case seven volunteers were between 23 and 29 years of age while one volunteer was above 40. The tests were performed at room temperature and average air humidity of 45 % ± 5 %.

To ensure reproducible measurement conditions, the skin of the volunteers at the intended electrode positions was cleaned using ethanol (96%) preliminary to the electrode application. After electrode placement the electrode-skin interface was allowed to stabilize during a period of 10 minutes. Adduction for the dry electrodes was provided by a custom-made elastic cap while the Ag/AgCl electrodes were fixated using medical-grade self-adhesive tape.

C. In-vivo electrode-skin interfacial impedance tests

During each impedance measurement only one MP electrode was tested. The dry MP electrode was placed on the forehead of the volunteers at Fp1 position according to the international 10-20 system for EEG electrode placement and a commercial Ag/AgCl ring electrode was applied at position Fp2 in combination with commercial electrolyte gel (Electro-Gel, Electro-Cap International Inc., USA). In addition to the dry electrode tests, a reference test using a second Ag/AgCl ring electrode placed at Fp1 position was performed.

The overall impedance between the two electrodes at Fp1 and Fp2 position was recorded for frequencies between 100 mHz and 10 kHz with a 7 mV (rms) AC probe signal. A Gamry series G 300 potentiostat was used, working in galvanostatic mode, in combination with Gamry EIS software (Gamry Instruments, USA). To guarantee volunteer safety, a custom-made battery-powered electronic safety interface was added between the active output of the impedance analyzer and the electrode. Although the applied test currents have always been below 10 µA, the safety interface was designed to immediately cut the connection if the current eventually overcomes a safety threshold of 100 µA. The complete setup is shown in Fig. 2.

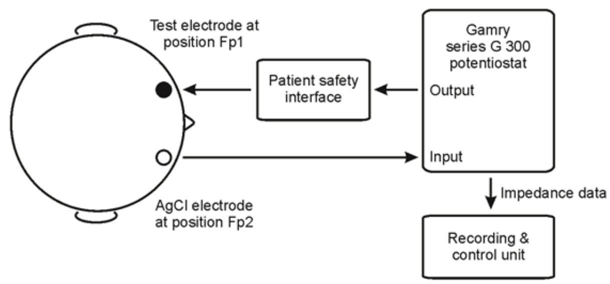

Figure 2. Measurement setup of the in-vivo electrode-skin interfacial impedance tests: Electrodes at Fp1 and Fp2 positions connected to the custom-made safety interface and the Gamry series G 300 potentiostat.

D. In-vivo EEG tests

For the EEG tests a conventional wet Ag/AgCl ring electrode was placed at position Fp2. Furthermore, a MP test electrode and an Ag/AgCl electrode were placed next to each other at position O2. In addition, a reference test using two Ag/AgCl electrodes at O2 position was performed. The wet electrodes were applied in combination with electrolyte gel while MP electrodes were used in dry condition only. Both occipital electrodes were connected to independent bipolar channels of a commercial EEG amplifier (Refa, Advanced Neuro Technologies B.V., The Netherlands). The second inputs of the bipolar channels were connected to the same frontal electrode. The measurement setup (Fig. 3) enables simultaneous recording of independent EEG signals. Thus, it is possible to directly compare signals acquired using conventional and a novel electrodes.

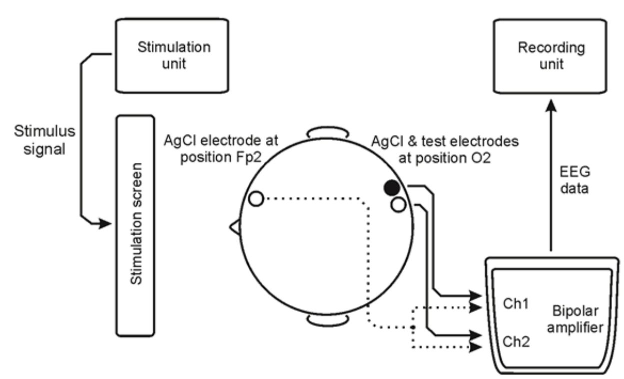

Figure 3. Measurement setup of the in-vivo EEG tests: Electrodes at Fp2 and O2 positions connected to two independent bipolar channels of a commercial biosignal amplifier.

During the in-vivo tests different EEG episodes were recorded including resting-state EEG, alpha activity, and eye-opening / eye-closing artifacts. Furthermore, a pattern reversal visual evoked potential (VEP) was recorded according to ISCEV standards.

All EEG signals have been subsequently filtered using a 24 dB Butterworth band pass with cut-off frequencies at 1 and 40 Hz as well as a 36 dB notch filter at 50 Hz. For evaluation of the VEP 250 stimuli have been averaged. Finally, the simultaneously recorded signals of the wet (*w*) and dry (*d*) electrodes are compared by means of the Root Mean Square Deviation (RMSD) and the Sperman's rank correlation (COR) according to Equation 1 and 2, respectively.

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

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

III. Results

A. Electrode-skin interfacial impedance

Fig. 4 shows the results of the interfacial impedance measurements. Capacitive characteristics are visible for all three compared electrode types. However, the dry electrodes clearly present stronger capacitive behavior than the conventional wet Ag/AgCl electrode. For the complete frequency range the conventional electrodes provide the lowest electrode-skin impedances. Furthermore, it is visible that increasing impedance values also correspond to increased variation among similar electrodes.

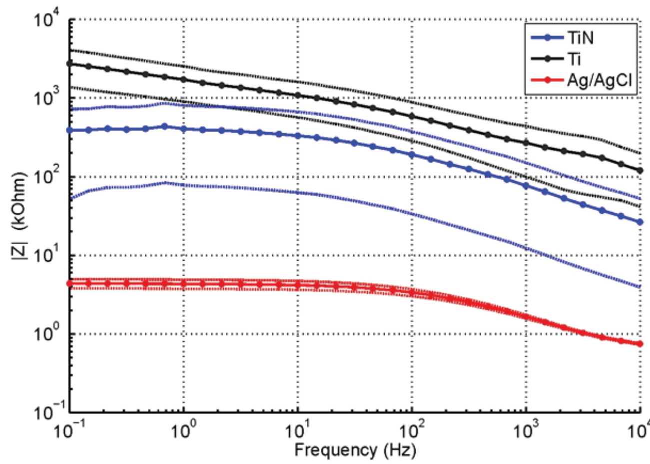

Figure 4. Results of the interfacial impedance measurements on eight volunteers for TiN (blue) and Ti (black) coated MP electrodes as well as conventional wet Ag/AgCl electrodes (red). Solid lines correspond to mean over all volunteers while dotted lines represent the standard deviation.

The mean impedance for Ag/AgCl electrodes at 10 Hz is 4.2 kOhm which is an expected result for well-prepared, cleaned skin. Additionally, due to the 10 minutes of stabilization time prior to the measurement, the skin is expected to be well hydrated. The mean impedances of the TiN and Ti coated MP electrodes at 10 Hz are 332.2 kOhm and 1 MOhm, respectively. This is above the impedance range of most conventional EEG amplifiers. However, the considerable variation visible for both electrodes enables impedances below 250 kOhm, thus allowing for EEG acquisition.

B. EEG signal quality

After signal processing and manual selection of 30 seconds long, artifact-free EEG episodes, the RMSD and COR values for all eight volunteers are calculated.

Fig. 5 depicts a box plot of the RMSD results. Although the results exhibit considerable variation, for each specific spontaneous EEG test the same ranking is visible. The median as well as lower and upper quartiles are always lowest for Ag/AgCl electrodes and highest for Ti coated MP electrodes. Comparing the different spontaneous EEG test conditions the RMSD increases with signal amplitude level. Lowest amplitude of resting EEG correspond to low RMSD while highest amplitude of eye opening / eye closing artifacts correspond to increased RMSD.

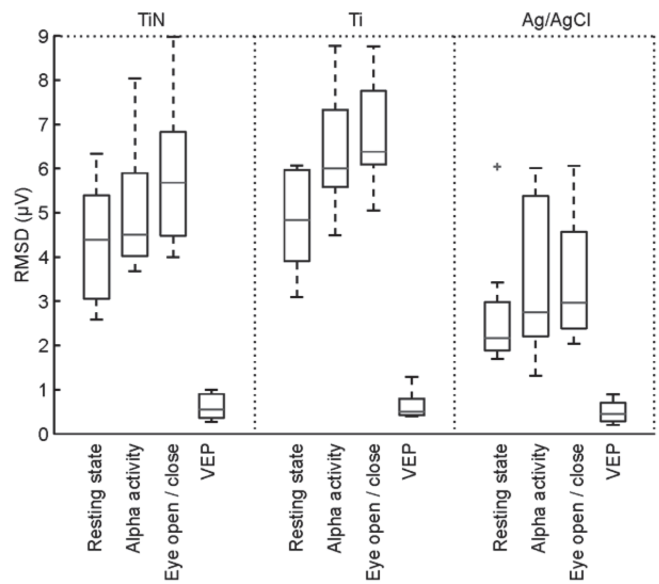

Figure 5. Box plot of the RMSD values for the simultaneously acquired EEG signals with dry MP and wet reference electrodes. Results of the TiN (left) and Ti (center) coated MP electrodes as well as wet Ag/AgCl electrodes (right) for eight volunteers.

In the VEP tests the RMSD is considerably reduced to values of 1.5 µV and below for all tested electrode types. Due to the fact that 250 stimuli episodes have been averaged prior to RMSD calculation, this emphasizes that most of the signal difference are caused by statistical signal components like interfacial or external noise.

Fig. 6 shows a box plot of the correlation values. An equivalent ranking as for the RMSD values is visible. Highest correlation values in spontaneous EEG correspond to Ag/AgCl electrodes, lowest correlations correspond to Ti MP electrodes. Furthermore, higher correlation values correspond to increased signal amplitudes. Thus, it is possible to summarize that deterministic signal components represented by higher amplitudes are reflected in both simultaneously recorded signals.

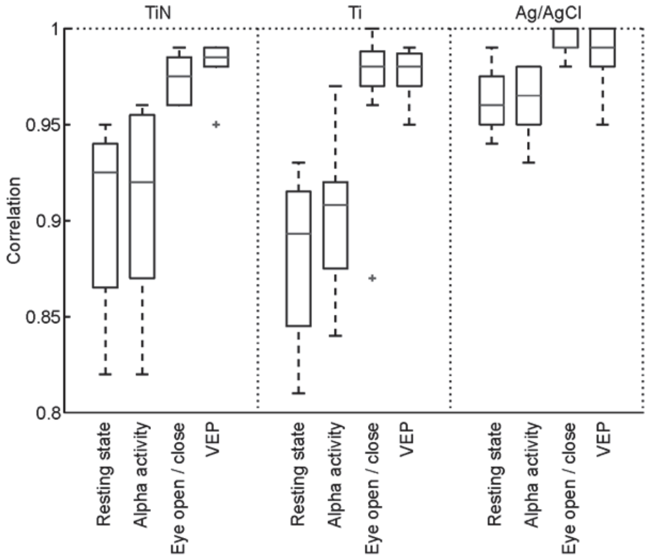

Figure 6. Box plot of the Spearman's rank correlation coefficients for the simultaneously acquired EEG signals with dry MP and wet reference electrodes. Results of the TiN (left) and Ti (center) coated MP electrodes as well as wet Ag/AgCl electrodes (right) for eight volunteers.

IV. DISCUSSION

The present study proved our developed MP electrodes to be able to reproducibly record EEG signals in multiple volunteers. The RMSD results for the dry MP electrodes – especially TiN – and the Ag/AgCl vs. Ag/AgCl reference tests are in the same order of magnitude. The actual difference between the RMSD values often is lower than the standard deviation, what demonstrates that it is possible to record signals with Ag/AgCl-comparable quality using dry MP electrodes. Although the impedance tests depict high and variable impedances for both MP electrodes, the acquisition of EEG signals using TiN electrodes was possible without increased preparation effort. However, an increased variability of the preparation process and results for the Ti coated MP electrodes was observed.

During the impedance and EEG tests a degradation of the sputtered TiN and Ti coatings was visible. Due to the fact that the EEG tests were performed prior to the impedance tests, this can explain the increased impedance values. Furthermore, delamination of the coating as well as micro-cracks on the pin basement due to mechanical stress was observed after more than two applications. These micro-cracks are promoted due to shape imperfections caused by the substrate prototype. Hence, micro-cracks and variable pin contact surface can increase interfacial impedance as well as susceptibility to movement artifacts and interfacial noise.

However, taking into account the fast and dry application as well as the low order of magnitude of the RMSD values the results especially for TiN coated electrodes are promising. Thus, the electrode substrate shape will be further optimized in order to decrease mechanical stress on the pin basement and tips. Furthermore, the coating process will be optimized in order to increase ductility and adhesion.

Additionally, the presented study will be extended by analyzing further coating materials and coating parameters. Finally, a complete evaluation of the electrode performance will be established by performing electrode-skin interfacial noise tests and analyzing noise and EEG data in the frequency domain.

V. CONCLUSION

A novel, flexible MP electrodes with two different, biocompatible coating materials was analyzed and their performance concerning electrode-skin interfacial impedance as well as EEG signal quality was evaluated in a multi-volunteer study. The performed tests provided promising results for further investigation. The proposed electrode concept will provide the technological base for a preparation-free multichannel measurement system for EEG.

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REFERENCES

[1] A. Searle and L. Kirkup, "A direct comparison of wet, dry and insulating bioelectric recording electrodes", Physiological Measurement, vol. 21, no. 2, pp. 271-283, May, 2000.

[2] P. Tallgren, S. Vanhatalo, K. Kaila et al., "Evaluation of commercially available electrodes and gels for recording of slow EEG potentials", Clinical Neurophysiology, vol. 116, no. 4, pp. 799-806, Apr, 2005.

[3] M. Oehler, M. Schilling, HD. Esperer, "Capacitive ECG system with direct access to standard leads and body surface potential mapping", Biomedizinische Technik, vol. 54, no. 5, pp. 329-335, 2009.

[4] B. Eilebrecht, A. Schommartz, T. Wartzek et al., "Mehrkanaliges EKG-Messsystem mit kapazitiver Patientenankopplung", Biomedizinische Technik, vol. 55, pp. 28-30, 2010.

[5] M. S. Fernandes, N. S. Dias, A. F. Silva et al., "Hydrogel-based photonic sensor for a biopotential wearable recording system", Biosensors & Bioelectronics, vol. 26, no. 1, pp. 80-86, Sep, 2010.

[6] P. Fiedler, S. Griebel, C. Fonseca et al., "Novel Ti/TiN Dry Electrodes and Ag/AgCl: A Direct Comparison in Multichannel EEG", IFMBE Proceedings of the 5th European Conference of the IFMBE, vol. 37, pp. 1001-1014, 2012.

[7] P. Griss, H.K. Tolvanen-Laakso, P. Merilainen et al. "Characterization of micromachined spiked biopotential electrodes", IEEE Transactions on Biomedical Engineering, vol. 49, no.6, pp. 597-604, 2002.

[8] CT. Lin, LD. Liao, YH. Liu et al., "Novel Dry Polymer Foam Electrodes for Long-Term EEG Measurement", IEEE Transactions on Biomedical Engineering, vol. 58, no. 5, pp. 1200-1208, 2011.

[9] C. Grozea, C.D. Voinescu, S. Fazli, "Bristle-sensors – low-cost flexible passive dry EEG electrodes for neurofeedback and BCI applications", Journal of Neural Engineering, vol. 8, no. 2, Apr, 2011.

[10] P. Fiedler, P. Pedrosa, S. Griebel et al., "Novel Flexible Dry PU/TiN-Multipin Electrodes: First Application in EEG Measurements", Engineering in Medicine and Biology Society, 2011 Annual International Conference of the IEEE EMBC, vol. 33, pp. 55-58, 2011.

[11] P. Fiedler, L. T. Cunha, P. Pedrosa et al., "Novel TiN_x-based biosignal electrodes for electroencephalography", Measurement Science and Technology, vol. 22, no. 12, 2011.

[12] P. Pedrosa, E. Alves, F.N.P. Barradas et al., "TiN_x Coated Polycarbonate for Bio-Electrode Applications", Corrosion Science, vol. 56, pp. 49-57, 2012.