Comparison of three types of dry electrodes for electroencephalography

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ABSTRACT
A potential new area of routine application for electroencephalography (EEG) is the brain-computer interface, which might enable disabled people to interact with their environment, based on measured brain signals. However, conventional electroencephalography is not suitable here due to limitations arising from complicated, time-consuming and error-prone preparation. Recently, several approaches for dry electrodes have been proposed. Our aim is the comparison and assessment of three types of dry electrodes and standard wet silver/silver-chloride electrodes for EEG signal acquisition. We developed novel EEG electrodes with titanium and polyurethane as base materials, which were coated with nanometer sized titanium-nitride films. Furthermore gold multi-pin electrodes were arranged on printed circuit boards. The results of the comparison of these electrodes with conventional wet silver/silver-chloride electrodes in terms of electrode impedances are presented, as well as open circuit potentials and biosignal measurements. Impedances were significantly higher for all dry electrode types compared to wet electrodes, but still within the measurement range of today's standard biosignal amplifiers. It was found that the novel dry titanium and polyurethane based electrodes show biosignal quality equivalent to conventional electrodes. In conclusion, the novel dry electrodes seem to be suitable for application in brain-machine interfaces.

1. INTRODUCTION

Electroencephalography (EEG) is a technique mainly used in the neurosciences and clinical neurological routine for detecting potential changes at the surface of the head, caused by electric activity inside the brain. The state of the art is characterized by the placement of 21 to 256 wet (gelled) silver/silver-chloride (Ag/AgCl) electrodes on the scalp, typically with the help of an EEG cap. The preparation procedure is lengthy (up to one hour) and requires well trained staff (typically medical technical assistants), and wear time is limited by the stability of the electrolytes (gels) [1], [2]. New application areas of EEG are in the field of brain-computer interfaces (BCI) or ambient assisted living (AAL). BCIs might enable handicapped persons to interact with their environment, based on measured brain signals [3], [4]. For such applications, specific EEG systems are needed, which may be applied by non-experts in a simple and fast way. Recently, the first EEG systems based on dry electrodes for BCIs were developed, which, however, included only a very limited number of channels [5], [6].
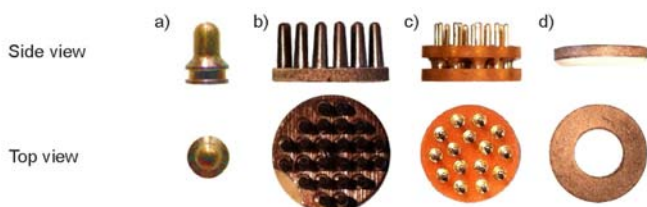
Figure 1. (a) Titanium single pin electrode, (b) polyurethane multi-pin electrode, (c) gold multi-pin electrode, and (d) conventional Ag/AgCl ring electrode. The pin shape allows hair layer penetration and causes a small indentation in the human scalp, which leads to an increased contact surface as well as reduced relative movements.

Our general aim is to develop a novel EEG system for home use with a high number of channels based on passive dry electrodes. Several approaches were developed for manufacturing the dry electrodes, including titanium (Ti) and polyurethane (PU) pin electrodes coated with titanium nitride (TiN) [7], [8]. Titanium nitride is chosen as coating material owing to its biocompatibility and chemical stability [9].

The aim of this paper is to compare the novel dry electrodes with standard wet silver/silver-chloride electrodes, in terms of electrochemical characteristics and signal acquisition performance. In addition to the TiN-coated electrodes, we also compare gold (Au) multi-pin electrodes recently proposed by other groups [10]. A comparative assessment of the different technologies concludes the study.

2. METHODS

2.1. Electrodes

The basic design requirements for dry contact electrodes are sufficient hair layer penetration, biocompatibility, electrochemical stability, and signal quality comparable to standard wet electrodes. Furthermore, our aim is to provide long term applicability, patient comfort, a cap ensuring sufficient electrode adduction, compatibility with conventional biosignal amplifiers, as well as ease of use and speed of preparation. Based on these criteria, three main types of electrodes were designed: (i) titanium pin electrodes, (ii) polyurethane multi-pin electrodes, and (iii) gold multi-pin electrodes. Figure 1 shows the three types of electrodes. The titanium pin electrodes and polyurethane multi-pin electrodes were coated with titanium nitride. The manufactured gold multi-pin electrodes are based on gold coated electronic precision brass pins soldered to a common epoxy baseplate.

Table 1 details the design parameters of the electrodes depicted in Figure 1. Note the different contact areas in row 4 of Table 1.

2.2. Electrochemical characterization

Electrode impedance characterization was performed for a frequency range of 5 Hz to 10 kHz using a Hewlett Packard
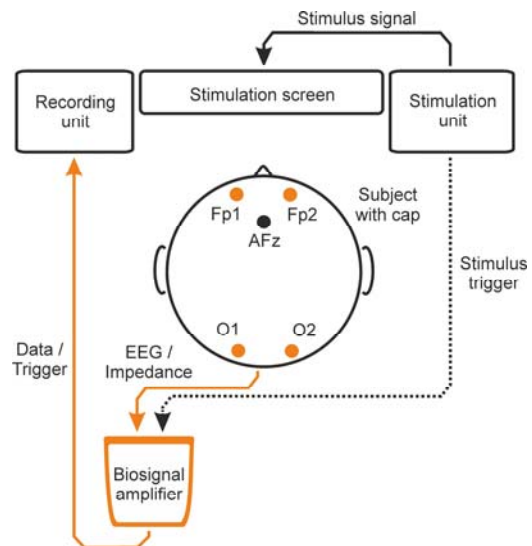

Figure 2. Bipolar measurement setup, showing the selected electrode positions. The stimulation screen was used for the visual evoked potential measurements. Patient ground: AFz; bipolar measurements: O1-Fp1 and O2-Fp2.

4192A LF impedance analyzer (Hewlett Packard Company, Palo Alto, USA). We used a standard four-point measurement setup in 0.9% NaCl solution. Open circuit potentials were measured in a 0.9% NaCl solution with an Agilent 34401A multimeter (Agilent Technologies, Santa Clara, USA), where an Ag/AgCl electrode served as reference (150 minutes after immersion into NaCl solution).

2.3. EEG signal acquisition

For EEG measurements, the electrodes were positioned according to the international 10-20 system [11]. Patient ground electrodes (always wet Ag/AgCl) were placed at the AFz position (Figure 2).

All measurements were performed with a set of Ag/AgCl electrodes adjacent (distance approx. 2.5 cm) to the dry contact electrodes (Figure 2), at two frontal and two occipital positions. For the Ag/AgCl electrodes reference measurement, two sets of Ag/AgCl electrodes were placed adjacent to each other (last column in Table 2). Test and reference signals were simultaneously recorded using two commercial amplifiers (Refa, ANT B.V., Enschede, The Netherlands), with common **average reference and a selected sampling rate of 512** samples/s. For all EEG tests, the room temperature was 22 °C and the relative air humidity was 35%. The electrode-skin interfacial impedance was recorded preliminary to the EEG tests, using the corresponding function of the EEG amplifier.

Three types of EEG activity were recorded in a healthy volunteer: resting state, alpha activity, and visual evoked potentials (VEP). Resting state and alpha activity are spontaneous EEG signals while the VEP is an averaged signal

Table 1. Electrode design parameters

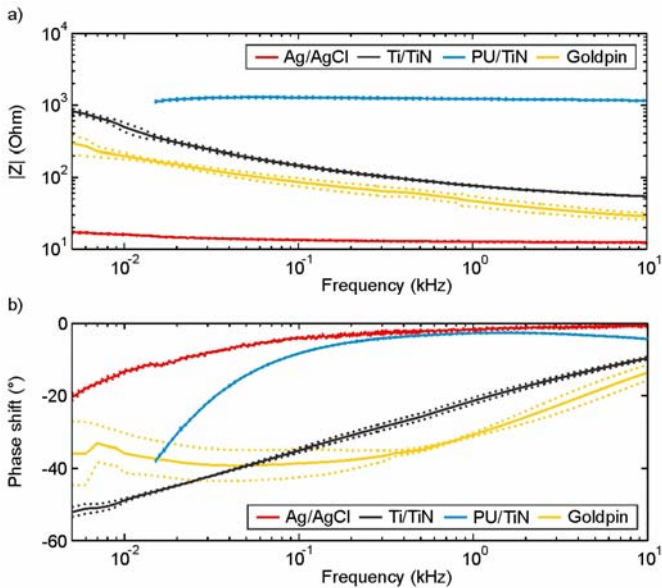|	Ti/TiN	PU/TiN	Au	Ag/AgCl
effective pin diameter (mm)	1.5	1.5	0.5	n.a.
effective pin height (mm)	2.5	6	3	n.a.
pin number	1	24	15	n.a.
approx. electrode contact surface (mm2)	3.5	85.1	6	42.5
approx. electrode weight (g)	0.05	0.73	2.21	0.61

Figure 3. Impedance spectra of the four types of electrodes: (a) absolute value and (b) phase of the impedance. Solid and dotted lines represent mean and STD of 10 measurements, respectively.

built to 250 single trials. Thus, temporal and frequency characteristics of the spontaneous and evoked activity are different. All signals were recorded using ASA software (ANT B.V., Enschede, The Netherlands), and the analysis was performed using MATLAB (The Mathworks Inc., Natick, USA). Data recorded using two sets of conventional Ag/AgCl ring-shaped electrodes (ANT B.V., Enschede, The Netherlands) served as reference.

3. RESULTS

Figure 3 shows the electrochemical impedance spectra of all four types of electrodes (mean over 10 measurements). The Ag/AgCl electrodes exhibited the lowest absolute values of the impedance, followed by the gold multi-pin electrodes, the titanium pin electrodes, and the polyurethane electrodes. For the gold multi-pin and the titanium pin electrodes, significant capacitive behaviour was observed, as demonstrated by the high impedances at low frequencies and lower impedances at higher frequencies.

For the phase responses, all electrodes showed a mainly decreasing phase shift with increasing frequency, corresponding to a capacitive behaviour. The Ag/AgCl electrodes showed the closest results to the mainly resistive behaviour, followed by the polyurethane pin electrodes, the gold multi-pin and the titanium
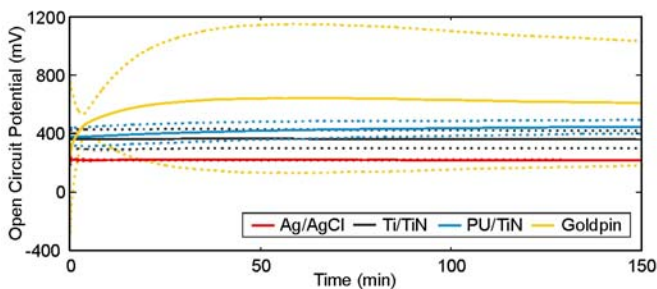

Figure 4. Open circuit potentials of the four types of electrodes recorded over 150 minutes after immersion into 0.9% NaCl solution. Solid and dotted lines represent mean and STD of 5 measurements, respectively.
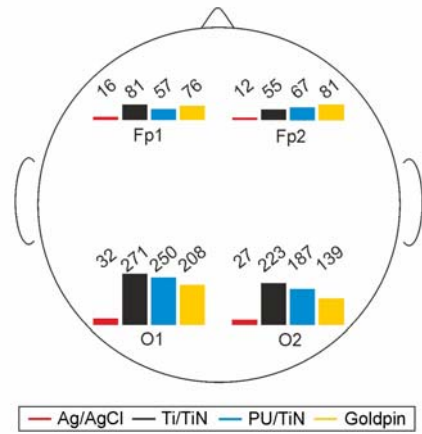

Figure 5. Measured impedances for a test set of four electrodes of each type. All values are in kΩ.

pin electrodes. However, due to measurement equipment restrictions, the polyurethane pin electrodes were not measured over the entire frequency range, which makes the values not comparable for the very low frequencies.

A stable and reproducible open circuit potential is important to avoid amplifier saturation problems, and strong signal drift limiting low frequency bandwidth. The mean open circuit potential (Figure 4) for the Ag/AgCl electrodes was 221.8 mV and the most stable in terms of mean STD (2.1 mV). Mean values of 610.8 mV $\pm$ 439.4 mV, 360.3 mV $\pm$ 63.3 mV and 422.2 mV $\pm$ 56.7 mV, were measured for the gold multi-pin electrodes, titanium pin electrodes and for the polyurethane pin electrodes, respectively.

Figure 5 presents the measured impedances at the volunteer's head, when 4 electrodes of the same kind were placed at the recording positions. The values for all dry electrodes were considerably higher than those for the Ag/AgCl electrodes. The dry electrodes showed also larger impedance variations.

The results of the EEG measurements are reported in Table 2. Between the two simultaneously recorded EEG sets,
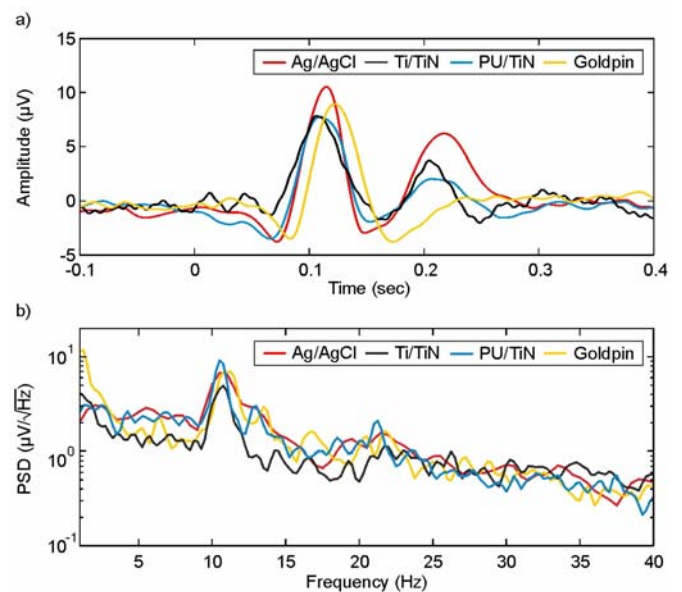

Figure 6. Overlay plots for channel O2 of different EEG recordings for all electrode types: a) VEP test results in time domain, and b) power spectral density of 10 seconds of EEG containing alpha activity.

Table 2. Mean RMSD and Correlation of the EEG data.

	EEG test	Ti/TiN	PU/TiN	Au	Ag/AgCl
RMSD (µV)	Resting EEG	6.9 ± 3.4	5.3 ± 0.6	6.1 ± 2.0	4.6 ± 2.1
	Alpha Activity	4.2 ± 1.8	4.4 ± 0.2	3.6 ± 0.6	3.9 ± 2.0
	VEP	0.6 ± 0.7	0.7 ± 0.3	1.9 ± 0.5	0.7 ± 0.4
Correlation (%)	Resting EEG	24 ± 19	59 ± 22	25 ± 13	58 ± 17
	Alpha Activity	76 ± 9	73 ± 9	73 ± 9	85 ± 2
	VEP	92 ± 10	95 ± 4	74 ± 22	94 ± 2

the root mean square deviation (RMSD) and the correlation coefficients corresponding to 30 seconds of data were computed, respectively, indicating important magnitude and morphological differences. The RMSD between the different electrodes, for the various signal types, showed similar values for all tested electrodes, except for the gold multi-pin electrodes at the VEP measurement.

As expected, the correlation is higher for the VEP, followed by the alpha activity. The lowest correlation is found for the resting state EEG.

According to Figure 6, similar results are also visible in overlay plots, for time and frequency domain. The main VEP components are exhibited in the recordings of all electrode types. The visible amplitude and latency variations are likely caused by slight variations of the electrode positions. In the PSD plot the alpha activity is clearly visible as a peak at approximately 11 Hz in all recordings. The gold multi-pin electrodes exhibit an increased drift, represented by higher PSD values for frequencies below 2 Hz.

4. DISCUSSION

The most relevant result from the above reported experiments consists in the fact that all the proposed types of dry electrodes allowed the recording of standard EEG. The signal traces and spectra were very similar to the ones of the simultaneously recorded Ag/AgCl electrode signals (Fig.5).

The differences in the RMSD in Table 2 were found to be similar for the different electrode types. This indicates that a main contribution to the RMSD stems from the spatial distance between the two compared sets of electrodes, and not from the materials differences. Exceptions are the VEP measurements with the gold multi-pin electrodes, where both the RMSD and the correlations showed deviating values. This can be explained by the difficulty in placing these electrodes at the back of the head, where a stronger curvature of the head makes it more difficult to achieve a good and reliable pin/scalp contact (compare also the length of the pins in Figure 1). At the same time, this region shows the most prominent mapping features in the VEP according to the activated brain areas.

The correlation values are also small for the resting state EEG (row four in Table 2). This can be explained by the fact that resting state EEG is highly variable in both time and spatial distribution. Hence, the spatial distances between the test and reference electrodes was too high to provide an adequate spatial sampling [7].

Table 3 summarizes the criteria for the comparison and the assessment of the different types of dry electrodes. All dry electrodes are easy and fast to apply and, according with bibliographic information, biocompatible (the printed circuit boards for the gold pins might be coated with biocompatible material). Due to the pin-like design, hair layer interfusion is achieved with all types of electrodes. Constant and sufficient electrode pressure on the skin is achievable for all types of electrodes, although patient comfort varies considerably. In this study, we considered conventional textile EEG caps for the PU/TiN and the gold multi-pin electrodes, while a novel actuator-based cap was used for the Ti/TiN pins. The average contact pressure was similar for both cap types. Considering the small size and adduction requirements, the novel dry electrodes enable high density multichannel electrode arrangements. These dense multichannel setups provide crucial spatial information about the brain activity, hence allowing for brain source reconstruction procedures in current [12] and new areas of application [3], [4].

Compared to wet Ag/AgCl electrodes, the bandwidth of dry electrodes is reduced. While Ag/AgCl electrodes can record potential differences starting from DC, dry electrodes, due to their capacitive behaviour at low frequencies, might not be used below about 0.5 Hz. The lower frequency limit depends on the

Table 3. Criteria for comparison and assessment of dry electrodes.

Criteria	Ti/TiN	PU/TiN	Au
Dry, passive, fast and easy application	Yes	Yes	Yes
Biocompatible materials	Yes	Yes	Pins only
Electrode shape for hair layer interfusion	Yes	Yes	Yes
Cap system tested	Adduction actuator	Textile	Textile
Signal quality equivalent to Ag/AgCl	0.5 – 40 Hz	0.5 – 40 Hz	3 – 40 Hz
Biosignal amplifier compatibility	High impedance	Yes	OCP fluctuations
Patient comfort	max. 1 h	> 1.5 h	max. 1 h

type of electrode and is still to be optimized. In principle, all types of dry electrodes considered here are compatible with state of the art biosignal amplifiers. The relatively high impedances might, however, in some recording situations, cause artefacts. To circumvent such problems online artefact detection may be suitable [13].

The electrode-skin impedance characteristics of the different electrodes are considerably influenced by their actual contact surface. The contact surface given in Table 1 was calculated based on the geometry of the pin tips. During application, variable contact surfaces occur depending on further parameters including hair interfusion, hair density and contact pressure. Hence, further investigations should address the variability of these influencing parameters in a larger group of volunteers. The influence of each parameter will be quantified separately with a sensitivity analysis in a future study.

There are several further differences for the dry electrode types. The price is lowest for the gold multi-pin electrodes and highest for the titanium pin electrodes. More important for multichannel EEG applications, where up to 256 electrodes are applied, is the weight of the electrodes. Here, the gold multi-pin electrodes exhibit the highest weight, followed by the titanium pin electrodes (when taking 24 pins per electrode into account). On the other hand, the polyurethane electrodes weigh only about 100 g for 256 electrodes. Furthermore, the mechanical flexibility of the substrate contributes to increased patient comfort while, at the same time, maintaining contact reliability (Table 3 last line). This renders the polyurethane electrodes very suitable for the application in long-term measurements.

5. CONCLUSIONS

We conclude that polyurethane based electrodes coated with titanium nitride are suitable for recording EEG in applications like brain-computer interfaces.

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