Clinical Neurophysiology 116 (2005) 799–806

www.elsevier.com/locate/clinph

Evaluation of commercially available electrodes and gels for recording of slow EEG potentials

P. Tallgren[a], S. Vanhatalo[a,b], K. Kaila[a], J. Voipio[a,*]

[a]*Department of Biological and Environmental Sciences, University of Helsinki, P.O. Box 65, 00014 Helsinki, Finland*
[b]*Department of Clinical Neurophysiology, University Hospital of Helsinki, Helsinki, Finland*

Accepted 8 October 2004
Available online 23 November 2004

Abstract

Objective: To test the applicability of different types of commercially available electrodes and electrode gels or pastes for recording of slow EEG potentials.

Methods: Experiments were carried out on six types of reusable electrodes (silver, tin and gold cup electrodes, sintered silver–silver chloride (Ag|AgCl), platinum, stainless steel), six disposable Ag|AgCl electrode models, and nine gels or pastes. We studied the parameters, which are critical in slow-potential recording, such as polarization, initial and long-term stability and low-frequency noise.

Results: The best results were obtained with the reusable sintered Ag|AgCl electrodes. The six disposable Ag|AgCl electrode models also proved to have appropriate electrical properties. Other types of reusable electrodes suffered from diverse degrees of polarization, baseline drift, low-frequency noise, high resistance, and changes in properties due to wear and tear. Seven out of nine gels or pastes contained a significant amount of chloride, which is a prerequisite for DC stability of Ag|AgCl electrodes, whereas the absolute concentration of chloride had little effect.

Conclusions: Direct current (DC) coupled recording of EEG is critically dependent on the choice of electrode and gel.

Significance: Our results provide rigorous criteria for choosing DC-stable electrodes and gels for DC-coupled or long time-constant AC-coupled recordings of slow EEG potentials.

Keywords: DC-EEG; FbEEG; EEG electrode; Intracranial electrode; Slow-potentials; Electrode gel; Polarization; Noise; Infraslow; Ultraslow; Super-slow; Multisecond

1. Introduction

Recent work has shown that a vast amount of information can be lost when recording EEG-signals using conventional AC-coupled (alternating current coupled; i.e. high-pass filtered) recording methods (Vanhatalo et al., 2004a). For instance, infraslow (also called ultraslow, super-slow, or multisecond) oscillations within the frequency range of 0.02–0.2 Hz are seen during nonREM sleep and they show a distinctive relationship with higher frequency EEG events (Vanhatalo et al., 2004b). Furthermore, long-lasting DC shifts are observed during awakening or falling asleep, or during changes of sleep stage (Marshall et al., 1994, 1998). In preterm babies, most of the total power of scalp recorded full-band EEG (FbEEG; see Vanhatalo et al., 2004a) is confined to frequencies much below 0.5 Hz, and the use of conventional high-pass filtering with a cut-off at 0.5 Hz causes severe distortion of the activity transients that are a characteristic feature of the EEG during this early stage of development (Vanhatalo et al., 2002). FbEEG has also been applied in studies on pathological states, and scalp recording of DC shifts during focal seizures (Ikeda et al., 1999; Vanhatalo et al., 2003a) holds promise as a novel tool in presurgical epilepsy diagnostics (Lagerlund and Gross, 2003; Barkley et al., 2003). With regard to their generation mechanisms, a significant contribution of a nonneuronal source has been demonstrated to underlie evoked DC shifts in healthy subjects (Vanhatalo et al., 2003b;

* Corresponding author. Tel.: +358 9 191 59858 fax: +358 9 191 59810.
E-mail address: juha.voipio@helsinki.fi (J. Voipio).

1388-2457/$30.00
doi:10.1016/j.clinph.2004.10.001

Voipio et al., 2003). Finally, it is worth pointing out that microvolt-level potential shifts lasting seconds and associated with various kinds of cognitive tasks and states have been subject to numerous studies (e.g. Birbaumer et al., 1990; Cui et al., 2000; Trimmel et al., 2001; Hinterberger et al., 2003).

Taken together, the above examples indicate that the tradition of recording EEG in AC-coupled mode ignores the true frequency distribution of EEG signals, and hence the interpretation of such data is based on severely distorted signals. Therefore, there is a need to establish reliable methods of FbEEG recording. Two approaches have been used in order to achieve this goal: genuine DC-coupled amplifiers (DC-EEG amplifiers), and AC-coupled amplifiers with a high–pass filter having a sufficiently long time constant (i.e. tens of seconds). While AC-coupled recording devices are convenient in that their response dynamics do not saturate, they will always cause distortion at low-frequencies and reject 'standing potentials', and, furthermore, they recover slowly from transient artifacts. In addition, slow EEG signals cannot be recorded properly with any type of amplifier unless the tissue–electrode interface is capable of transferring electrical signals to the amplifier without distortion.

The purpose of the present study was to investigate the applicability of commercially available electrodes and electrode gels or pastes (named hereafter as gels) in studies of slow EEG signals (<0.5 Hz). The high-frequency properties of all electrode types are satisfactory and are considered elsewhere (Onaral et al., 1984; Eggins, 1993; Huigen et al., 2002).

2. Materials and methods

We examined six reusable electrode types made of different materials and six different disposable silver–silver chloride (Ag|AgCl) electrodes: gold (F-E5GH-48; Grass-Telefactor, West Warwick, RI, USA), tin (E21-9; Electro-Cap International, Eaton, OH, USA), silver (C12-434; Technomed Europe, Maastricht, The Netherlands), sintered Ag|AgCl (E220N-LP; In Vivo Metric, Healdsburg, CA, USA), platinum (T-WS-6P; Ad-Tech Medical Instrument Corporation, Racine, WI, USA), stainless steel (T-WS-6; Ad-Tech Medical Instrument Corporation), and disposable Ag|AgCl electrodes Neuroline 700, Neuroline 710, Neuroline 720 (Ambu A/S, Ballerup, Denmark), Nicolet (Nicolet Biomedical Inc., Madison, WI, USA), 13952E (an ECG electrode; Philips Medical Systems, Andover, MA, USA) and Blue Sensor NF-50K (an ECG electrode; Ambu A/S). As emphasized below, the 'gold' electrodes have a silver body that is plated with a thin layer of gold. Gold, tin and silver cup electrodes were of the same size (diameters 9–10 mm), and the sintered electrode had a flat spherical AgCl surface (diameter 4 mm). The platinum and stainless steel electrodes were subdural strip electrodes with an exposed contact area diameter of 3 mm. All electrodes were initially new and unused. During the course of the study, reusable electrodes were cleaned with gentle brushing under running distilled water and dried in air. All disposable electrodes were of chlorided silver and all but NF-50K contained a pre-applied electrode gel.

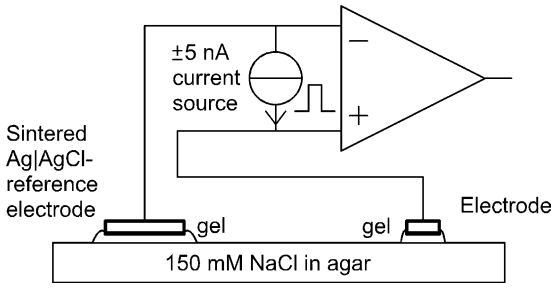

Fig. 1. A schematic illustration of the experimental arrangement used to test the polarization of electrodes upon prolonged constant current pulses of ±5 nA. Noise and stability measurements were carried out using a similar arrangement but no current was applied. At least 1 h was allowed for stabilization of the reference electrode before the experiments were started (see Section 2).

The electrodes were mounted with gel (unless otherwise mentioned, Signa Gel; Parker Laboratories Inc., Fairfield, NJ, USA) on a flat block of 2.5–3% agar made in physiological NaCl (150 mM), as schematically shown in Fig. 1. Gel was not added when using the four pre-gelled disposable electrode types. A large sintered Ag|AgCl electrode (diameter 12 mm; In Vivo Metric E-226) was used as a reference electrode in all experiments. It was mounted with Signa Gel and allowed to stabilize for at least 1 h before the experiments were started. Control measurements were carried out to make sure that the total resistance of the NaCl–agar block and the reference electrode was always small (<1 kΩ). The experiments on stainless steel and platinum electrodes were carried out with the electrodes submerged in physiological NaCl. After stabilization of electrode potentials, very small (cf. Geddes and Roeder, 2001) constant current pulses of ±5 nA lasting for over 100 s were applied and the voltage responses were recorded using a purpose-designed DC-coupled amplifier (long-term stability better than 1 μV/h, bandwidth 0–160 Hz). Voltage responses to three positive and three negative current pulses were converted to resistance and averaged. Signals were typically sampled at 150 Hz with a 2.4 or 4.8 μV resolution. The software for data recording and analysis was programmed under Labview (National Instruments, Austin, Texas, USA).

Electrode impedances at 20 Hz were measured with the DC-coupled amplifier using voltage responses to a sinusoidal current with a peak amplitude of 1.4 μA. Low-frequency noise measurements were made in AC mode with long time constant ($\tau > 80$ s) RC-high-pass filters at amplifier inputs. Electrode offset voltages were measured using a high-quality digital multimeter (HP/Agilent 34401A; Agilent Technologies, Palo Alto, CA) which has an input resistance of >10 GΩ.

The following electrode gels were tested: Signa Gel (Parker Laboratories Inc., Fairfield, NJ, USA), Spectra 360 (Parker Laboratories Inc.), Elektrodipasta comp (Berner Ltd, Helsinki, Finland), Ten20 (D.O. Weaver and Co, Aurora, CO, USA), Electro-Gel (Electro-Cap International, Eaton, OH, USA), EC2 (Grass Astro-Med Inc., Warwick, RI, USA), Electrode Jelly (Rochester Electro-Medical, Inc., Tampa, Fl, USA), Abralyt 2000 and Abralyt HiCl (Falk Minow Services, Herrsching, Germany). Spectra 360 and Abralyt 2000 are specified by their producers as chloride-free gels. Abralyt HiCl has been discontinued recently, but it was included to provide a comparison gel for Abralyt 2000 from the same manufacturer. Electrode potentials with different gels were recorded using four Ag|AgCl electrodes (E220N-LP) in each experiment and with the same gel also in the reference. Drying of the agar block was minimized by covering it with a lid.

Rough estimates of the chloride concentrations of gels were measured using a chlorided silver wire against a KCl–agar bridge reference using calibration solutions with various NaCl concentrations (0.01 to 1 mol/l). Results are presented as mean ± SEM.

3. Results

3.1. Impedance and offset voltage

Electrode impedance reflects the electrode's capability to transfer signals at a given frequency (Geddes and Baker, 1968). All electrode types had an impedance of <1 kΩ at 20 Hz between the electrode and the NaCl–agar block (or NaCl solution, see Section 2). Typical absolute values of electrode offset voltages (at steady state after 20 min) against the Ag|AgCl reference were: sintered Ag|AgCl <5 mV (see also Trimmel et al., 1982), gold 20 mV, and tin ~500 mV. Offset voltages of silver electrodes were highly variable, ranging from 30 to 150 mV in fresh electrodes to roughly 20 mV or below in used and worn electrodes. The offset voltages of platinum and stainless steel were extremely high indicating substantial spontaneous polarization, and hence meaningful values cannot be given. Large offset voltages were associated with a large variability: for instance, the potential differences between tin–tin electrode pairs often exceeded 100 mV.

3.2. Resistive vs. capacitive behavior

Conductive charge transfer across an electrode–solution interface is seen as its resistive behavior, whereas capacitive coupling dominates in the absence of charge-transferring electrode reactions (Geddes and Baker, 1968). Three kinds of voltage responses were observed upon prolonged constant current pulses of very low amplitude (±5 nA). First, as expected, the response of the sintered Ag|AgCl electrodes to current was very small, indicating a mean

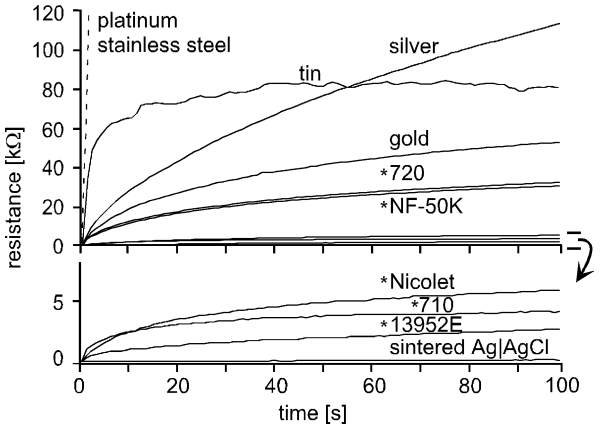

Fig. 2. Current-induced polarization of electrodes, shown as apparent resistance against time. Typical responses of single tin, gold, silver, sintered Ag|AgCl and disposable Ag|AgCl (marked with an asterisk) electrodes to constant current pulses of ±5 nA. Subsequent current pulses were of alternating polarity, and six voltage responses were divided by the injected current and averaged. The responses of platinum and stainless steel electrodes went almost immediately out of scale because of rapid polarization (shown schematically with the dashed line). The lower panel shows recordings with higher amplification made with the sintered Ag|AgCl and three disposable Ag|AgCl electrode models, as indicated by the arrow.

resistance of <1 kΩ ($n=4$; measured at 100 s after current onset). Disposable Ag|AgCl electrode types ($n=2$–4) gave smoothly developing voltage responses, with near steady state values at 100 s corresponding to mean resistances of ≤ 1 to 33 kΩ (see Fig. 2). This range of resistances of the Ag|AgCl electrodes could not be accounted for by differences in their apparent active surface areas, although the resistances of the two smallest electrodes (720 and NF-50 K; range 10–33 kΩ) were significantly higher than those of the other disposable electrodes (range ≤ 1 to 6 kΩ; $p<0.003$, unpaired t-test). Second, tin and gold electrodes charged up to higher potential levels indicating poor conductive charge transfer (see Geddes and Baker, 1968) across the electrode interface. However, responses to current were of roughly similar shape and magnitude in both current directions and gave resistances of 29–80 kΩ ($n=4$) and 50–92 kΩ ($n=3$) for tin and fresh gold electrodes, respectively (Fig. 2). The resistances of worn gold electrodes showed a much larger variation with a minimum at 4 kΩ ($n=6$). As can be seen from the averaged specimen traces in Fig. 2, the potential shifts upon current pulses with tin electrodes were not smooth and monotonic but showed random fluctuations. The responses of silver electrodes were initially large (20–122 kΩ, mean 61 kΩ, $n=6$) but they decreased during repeated experiments, a result that can be accounted for by spontaneous formation of AgCl onto the silver surface (see below). Third, a capacitive, nonconductive behavior was seen with platinum and stainless steel which showed a linear charging-up of the electrode–gel interface at a rate that was orders of magnitude faster than with the other electrode types.

The observed progressive change not only in the performance but also in the color of silver electrodes indicated that spontaneous formation of AgCl took place on the silver surface during repeated experiments. This was further verified as follows. Passing a constant current of −1 mA through worn silver electrodes immersed in 150 mM NaCl solution re-established the shining silver color and the electrical properties (offset voltage, resistance) of fresh silver electrodes ($n=3$). In fact, offset voltages as high as −150 to −600 mV were measured after such a treatment. A similar kind of gradual attainment of reversible electrode behavior during repeated series of experiments was characteristic to gold electrodes. These electrodes have a silver body coated with a thin layer of gold. Deterioration of the gold coating was evident in microscopic inspection of worn gold electrodes, partially exposing the silver body to direct contact with gel and thereby allowing formation AgCl, which readily accounts for the observed changes in electrode properties.

3.3. Drift and low-frequency noise

Slow spontaneous change in electrode polarization is a potential source of drift in DC recordings. Variations in the rate of drift are seen as low-frequency noise. We compared the stability of tin, gold, silver (five electrodes of each type), and sintered Ag|AgCl electrodes (nine electrodes) in the absence of injected current against a sintered Ag|AgCl reference that had been allowed to stabilize with gel on the NaCl–agar block for over one hour. The absolute values of the initial rate of drift immediately after mounting of the electrodes with gel on the NaCl–agar block were much smaller with sintered Ag|AgCl than with the other reusable electrode types (Fig. 3). Significant stabilization to a mean drift rate of 121±33 μV/min took place in 15 min, and at 60 min from beginning the rate of drift was only 18±7 μV/min. These data indicate that adequate stabilization of sintered Ag|AgCl electrodes can be easily achieved in routine clinical applications (see also Vanhatalo et al., 2003a; Trimmel et al., 1982). The stabilization of gold and silver electrodes, all of which had been used in experiments before, started with an initial rate of drift of around 1.5 mV/min (see Figs. 3 and 4) and fell in 60 min to 62±23 μV/min (gold) and to 166±77 μV/min (silver). The apparently striking similarity of the reusable gold and silver electrodes is likely to be due to the formation of AgCl on their silver bodies (see above). Tin electrodes did not stabilize to a level that would be acceptable in DC-coupled EEG measurements (see Fig. 3).

It is worth pointing out that the drift values given above do not only reflect a slowly changing potential difference across the electrode–gel interface, but any changes in the liquid-junction potential (Ammann, 1986) between the gel and the NaCl–agar block (or skin in real EEG recording) will also be seen as drift. A lower limit of 0.8 mV for the initial value of this liquid-junction potential was estimated

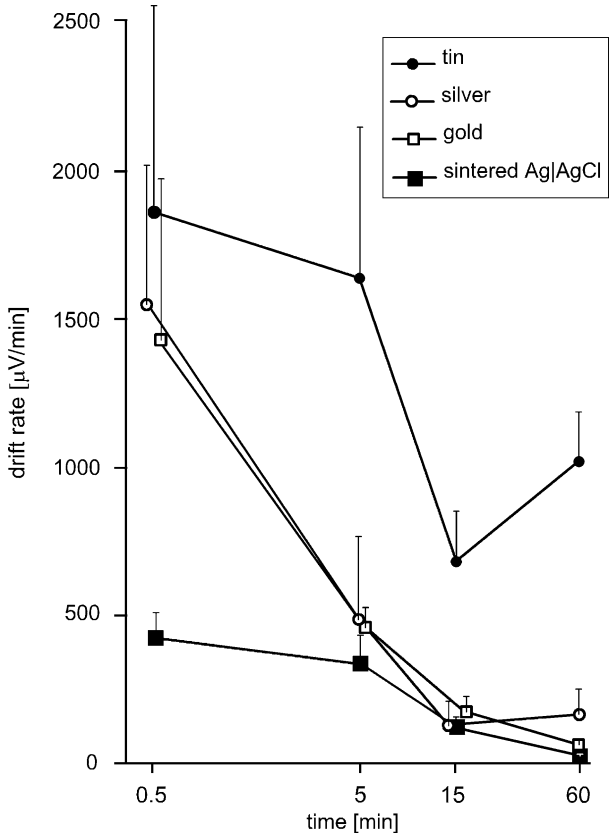

Fig. 3. Stabilization of electrode potentials. Mean rates of baseline drift + SEM of tin ($n=5$), silver ($n=5$), gold ($n=5$) and sintered Ag|AgCl ($n=9$) electrodes measured at different time points after mounting of the electrodes on the NaCl-agar block.

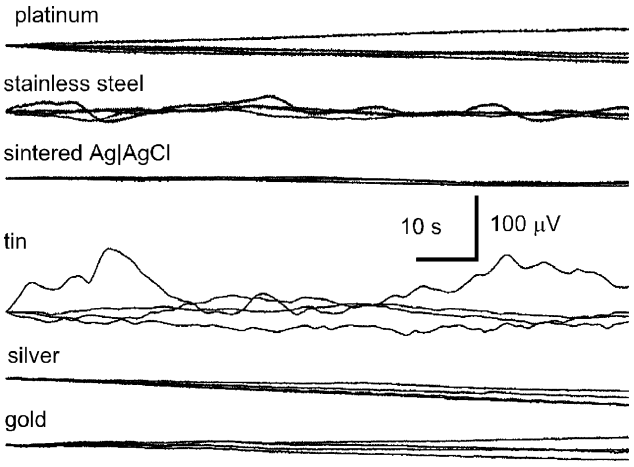

Fig. 4. Low-frequency noise of the six reusable electrode types after 1 h of stabilization with gel on the NaCl-agar block. Traces obtained using three to four electrodes of each type have been superimposed. The silver electrode data are typical for worn electrodes. Disposable Ag|AgCl electrodes did not differ markedly from sintered Ag|AgCl electrodes and, therefore, their traces are not shown. The recordings were carried out with RC high-pass filters at the amplifier inputs having a time constant of 80 s, which corresponds to a high-pass cut-off frequency of 0.002 Hz.

on the basis of the measured Cl^- concentration of the electrode gel (see below) and using the Henderson liquid junction potential equation (Ammann, 1986). This value suggests that a slow dissipation of liquid junction potentials may account for a significant fraction of the lowest drift rates observed in the present study.

We next carried out measurements of low-frequency noise in AC-mode with high-pass cut-off frequency at 0.002 Hz to abolish effects mediated by polarization. Even after letting the electrodes stabilize for one hour, tin and stainless steel showed slow spontaneous fluctuations of up to 100 μV/10 s (with tin up to 1 mV/10 s when using cut-off at 0.0002 Hz; not illustrated), which significantly limit their use in slow-signal detection (Fig. 4). Ag|AgCl electrodes, as well as platinum, silver and gold electrodes had a low noise level. Our results are in line with other studies (Fernandez and Pallas-Areny, 2000) in that small offset voltages are associated with a small noise level.

3.4. Long-term stability of Ag|AgCl electrodes

The results described so far clearly indicate that out of the six electrode materials studied only Ag|AgCl has the properties that are required for reliable recording of slow EEG signals. Therefore, we next studied the long-term stability of the sintered Ag|AgCl electrode type and that of the six disposable Ag|AgCl electrodes. Fig. 5 shows continuous recordings lasting up to 5.5 h from mounting of the electrodes on the NaCl–agar block. Although some differences between electrodes can be seen, it is evident that the long-term stability after the first 20–30 min of all these Ag|AgCl electrodes is adequate for monitoring of slow EEG events with a duration of up to at least tens of seconds. It is worth pointing out that out of the seven electrode models used in this stability test, sintered Ag|AgCl and NF-50K were gelled at the beginning of the recording session while the other electrodes are of pregelled type. However, this does not seem to account for the differences in initial stabilization of electrode potentials (see Fig. 5).

When using silver electrodes with a thin surface layer of AgCl in long-term DC-coupled EEG-recordings, a net leakage current directed from gel to the electrode might slowly use up all AgCl from the electrode surface and make the electrode unstable. We tested the six disposable Ag|AgCl electrode types in this respect by exposing them to prolonged DC currents with low amplitude. No detectable increase noise level was found after a current of 5 nA had been passed from gel to electrode for 10 min. A pronounced increase in electrode potential or noise level took place only after passing a current of 0.1 mA for at least 5 min through the smallest disposable electrodes (720 and NF-50K), and the corresponding time was longer with the other electrodes (not illustrated). This indicates that the six disposable electrodes types are not prone to electrolytically loose their AgCl coating under appropriate recording conditions. Two sintered Ag|AgCl electrodes were used in a similar test to verify the *a priori* evident result, that prolonged net currents of low amplitude do not cause a detectable change in their performance.

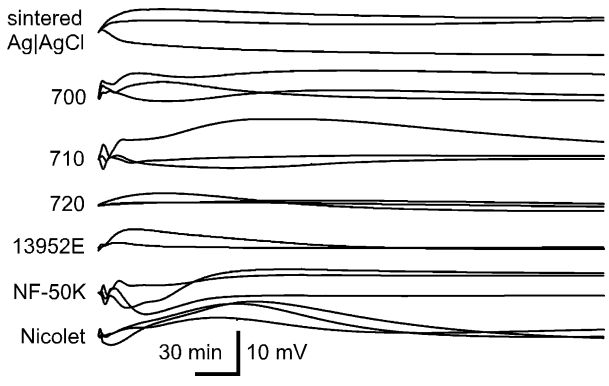

Fig. 5. Long-term DC-stability of Ag|AgCl electrodes in continuous recordings starting from mounting of the electrodes on the NaCl–agar block. Superimposed traces recorded using two to three electrodes of each type have been offset to start from the same level.

3.5. Gels

Finally, we wanted to find out whether the commercially available electrode gels have an influence on electrode potential stability. We first obtained rough estimates of the Cl^- concentration in the nine commercially available gels (see Section 2). Two of the products are sold as chloride-free gels. Spectra 360 was found to be devoid of Cl^-, whereas a low level of Cl^- was detected in Abralyt 2000 (15 ± 3 mM, $n=7$) (Fig. 6). The Cl^- concentration in the other gels varied from 0.8 to 2.1 M. Stability was monitored using sintered Ag|AgCl electrodes ($n=4$ for each gel) for reasons that are obvious in light of the results presented so far. Electrode potentials underwent significant initial drifts which varied in amplitude and duration between the gels (Fig. 7A). As could be expected on the basis of the requirement for Cl^- anions for stable operation of Ag|AgCl

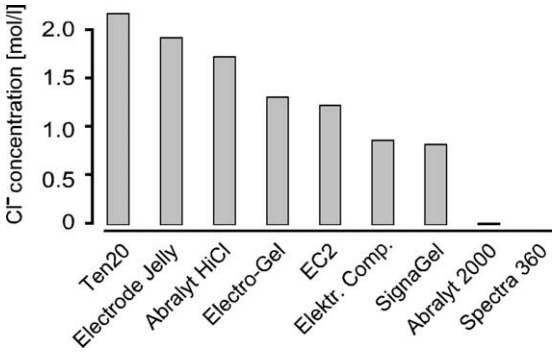

Fig. 6. Concentrations of chloride in the nine electrode gels. Note presence of a low amount (15 ± 3 mM, $n=7$) of Cl^- in Abralyt 2000.

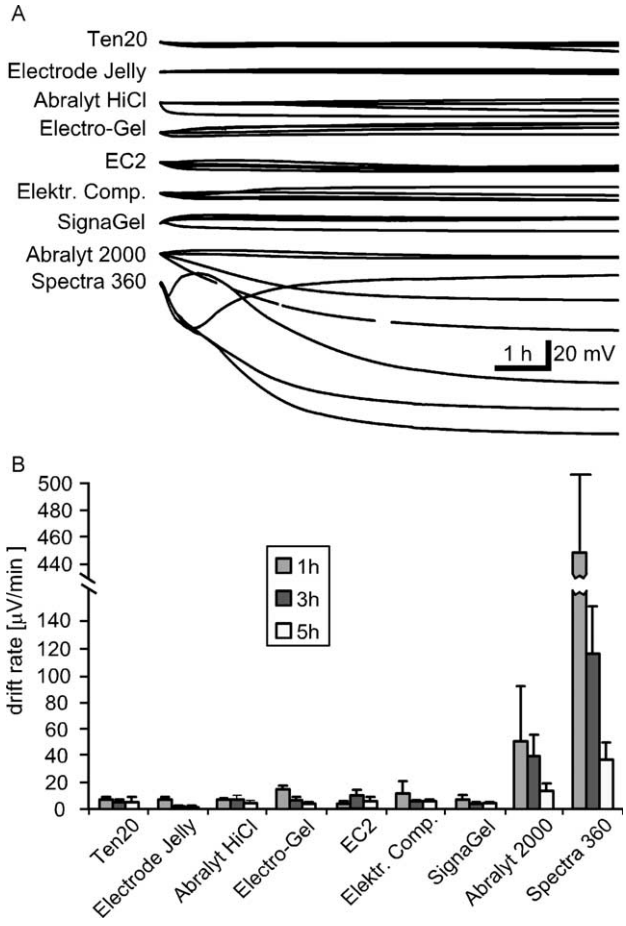

Fig. 7. Effect of gel on long-term stability of sintered Ag|AgCl electrodes. (A) Superimposed continuous recordings starting from mounting of four electrodes with one type of gel on the NaCl–agar block and offsetting the initial baselines to zero. The chloride-free gel Spectra 360 promotes significant drifts resulting in a variation of electrode potentials that is an order of magnitude higher than observed with any of the Cl^- containing gels. Abralyt 2000, which was found to contain a small amount of Cl^-, shows an intermediate tendency to promote drifting. Note that baselines with the Cl^- containing gels are very stable after leveling off of the initial drift. (B) Quantification (mean + SEM) of the drift rates at 1, 3 and 5 h from the data shown in A.

electrodes, drift rates exceeding 1 µV/s were often observed with Cl^- free gels (Spectra 360 and Abralyt 2000) at 1 h from applying the gel, and an acceptable stability was not attained even after hours of recording (Fig. 7B). The large offset potentials (Fig. 7A) and drift rates (Fig. 7A and B) indicate that Cl^- free gels are not appropriate for recording of slow signals with Ag|AgCl electrodes and a DC-coupled amplifier. It is also evident from Fig. 7A that offset voltages generated between individual Ag|AgCl electrodes during a recording session of hours will usually remain within 1–10 mV with the Cl^- containing gels and they are roughly an order of magnitude smaller than when using the Cl^- free gels. An adequate recording stability can be achieved in most applications with any of the seven Cl^- containing gels, and the choice of the most applicable gel may be based on criteria not addressed in this study.

4. Discussion and conclusions

The present study was undertaken in order to evaluate the applicability of common commercially available electrodes and gels in recording of slow and infraslow EEG signals. The results provide a solid basis for selecting electrodes and gels in applications where either DC-coupled or long time-constant AC-coupled recording devices are being used.

4.1. Properties of different types of electrodes and gels

Our results indicate major differences between the different electrode types in their performance at low-frequencies (Table 1). Excellent DC-stability, superior low-frequency noise and lowest resistance makes Ag|AgCl the only electrode type that can be reliably used in work aimed at detection of infraslow EEG-events. The risk of amplifier saturation due to amplification of electrode offset voltages as well as possible generation of artifactual signals upon changes in amplifier bias current (i.e. polarization) are further factors that strongly support the use of Ag|AgCl electrodes with DC-coupled recording devices. This result is in line with the well-known reversible electrode reaction that is responsible for conductive charge transfer between Ag|AgCl and a Cl^- containing solution (e.g. Geddes and Baker, 1968):

$$Ag(s) + Cl^-(aq) \rightleftarrows AgCl(s) + e^-.$$

This reaction also readily accounts for the observed need of Cl^- in gels. Sintered Ag|AgCl electrodes had the best performance in all respects, but disposable Ag|AgCl electrodes were found to be applicable for slow-potential recording as well.

Although the present results do not argue against using tin electrodes in conventional EEG applications, this material turned out to suffer from a number of drawbacks at low-frequencies. These included poor DC-stability, high resistance and tendency to become polarized. Furthermore, the large and variable offset voltage manifests itself as significant low-frequency noise and pronounced fluctuations in the drift rate, which may rule out the use of tin electrodes even in long time constant AC-coupled recordings of slow EEG signals.

Coupling across the electrode–solution interface in platinum and stainless steel electrodes was capacitive, and these electrodes underwent polarization and hence saturated the DC-coupled EEG-amplifier. Both electrodes had a low impedance at higher frequencies, but only stainless steel electrodes suffered from noise in the long time-constant AC-coupled recording mode.

Fresh and used/worn silver electrodes showed striking differences in their performance. While fresh silver electrodes were unstable and had large offset voltages, worn electrodes approached the behavior of Ag|AgCl. This change was caused by spontaneous formation of AgCl on

Table 1
Summary of the properties of different types of electrodes when used in combination with a chloride containing gel

Electrode	Offset voltage, resistance and polarization	Rate of drift	Noise level	Suitability for DC-coupled recording	Suitability for long time-constant AC-coupled recording
Sintered Ag|AgCl[a]	Very low	Very low	Low	Excellent	Excellent
Disposable Ag|AgCl[b]	Low	Very low	Low	Good	Excellent
Silver[c]	Variable	Variable	Low	Poor	Good
Gold-plated silver[d]	Variable	Variable	Low	Poor	Good[e]
Platinum[f]	Very high	n.a.[g]	Low	Poor	Good[e]
Stainless steel[h]	Very high	n.a.[g]	Medium	Poor	Medium
Tin[i]	High	High	High	Poor	Poor

[a] E220N-LP (In Vivo Metric).
[b] Neuroline 700, 710 and 720 (Ambu A/S), Nicolet (Nicolet Biomedical Inc.), 13952E (Philips Medical Systems), Blue Sensor NF-50K (Ambu A/S).
[c] C12-434 (Technomed Europe).
[d] F-E5GH-48 (Grass-Telefactor).
[e] See discussion for details.
[f] T-WS-6P (Ad-Tech Medical Instrument Corporation).
[g] Not applicable because of very rapid polarization.
[h] T-WS-6 (Ad-Tech Medical Instrument Corporation).
[i] E21-9 (Electro-Cap International).

the electrode surface, evidenced by a change in colour and reversal of both effects by electrolytic cleaning of the electrode's surface. Since such a spontaneous process does not necessarily generate a uniform, homogenous AgCl surface layer, it would be difficult to predict how silver electrodes perform in low-frequency measurements.

Initially, we did not assume to find major differences between gold and platinum electrodes since both of these metals are chemically inert and thus provide only a capacitive connection to gel. However, gold electrodes showed to some degree properties of a reversible electrode. A likely explanation is related to the structure of the gold electrode used in this study, which is a silver body plated with a thin layer of gold. Fractures and deterioration of the gold layer were seen under microscopic inspection of worn electrodes, which, upon precipitation of Cl^- onto the exposed silver surface, will result in spatial heterogeneity in electrode potential generation and fluctuations of the detected signal (Aronson and Geddes, 1985). Therefore, our results speak against the use of this kind of gold electrodes in either DC- or AC-coupled recording of infraslow EEG events.

4.2. Prerequisites of DC-stable EEG recording

As discussed above, the present results indicate that an appropriate stability in DC-coupled EEG recording can be only achieved when using Ag|AgCl electrodes and a Cl^- containing gel. However, there are other factors that have to be taken into account when performing DC-coupled EEG recordings on scalp. The skin is a significant source of sustained and slowly changing potentials. Therefore, perforation of skin under recording electrodes has been used to short circuit such signals that could otherwise contaminate and even dominate EEG signals at low-frequencies (Picton and Hillyard, 1972; Cowen, 1974; Vanhatalo et al., 2003a; Voipio et al., 2003). Ag|AgCl electrodes record not only voltage signals but they are sensitive also to changes in Cl^- concentration. Sweating, as well as drying of the electrode gel, may change the Cl^- level sensed by the electrode. In order to minimise this source of artifacts, Ag|AgCl electrodes have been equipped with a cavity that is large enough to contain a sufficient amount of gel in order to significantly slow down changes in Cl^- concentration at the gel-AgCl interface (Trimmel et al., 1982; Bauer et al., 1989; Vanhatalo et al., 2003a; Voipio et al., 2003). Although the stability test used in this study did not reveal any clear differences between the seven Cl^- containing gels, they may differ in the degree of irritation and discomfort when applied on perforated skin (e.g. Tam and Webster, 1977). Finally, insulation of the external surface of the electrode body protects the electrode signal against contact-induced artifacts, and a low electrode body design helps in reducing movement artifacts.

4.3. Long time-constant AC-coupled recording of infraslow EEG events

The nonpolarizing Ag|AgCl is the only electrode material enabling genuine DC-coupled recording of EEG. However, detection of slow signals can also be achieved using polarizing metal electrodes in combination with an AC-coupled amplifier, provided that the time constant of the high-pass filter at the amplifier input is long enough (preferably 5–10 times higher than the duration of the EEG response of interest). If this approach is attempted, several precautions need close attention: (1) The coupling capacitance across the electrode–gel interface is in series with the amplifier input circuit and, if not high enough, may significantly decrease the effective time constant. (2) The electrode must have a low noise level at the low-frequencies of interest (see Fig. 4). (3) Transient polarization artifacts

generated by, e.g. movement of electrodes on scalp may have a high amplitude, and they fade out very slowly. Therefore, AC-coupled recording of infraslow EEG events is advisable only in applications where suitable nonpolarizing electrode models are not available, such as in intracranial recordings.

Acknowledgements

This work was supported by grants from the Academy of Finland and from the Sigrid Juselius Foundation.

References

Ammann D. Ion-selective microelectrodes: principles. Design and Application. Berlin: Springer-Verlag; 1986.

Aronson S, Geddes LA. Electrode potential stability. IEEE Trans Biomed Eng 1985;11:987–8.

Barkley GL, Baumgartner C. MEG and EEG in epilepsy. J Clin Neurophysiol 2003;20:163–78.

Bauer H, Korunka C, Leodolter M. Technical requirements for high-quality scalp DC recordings. Electroenceph Clin Neurophysiol 1989;72:545–7.

Birbaumer N, Elbert T, Canavan AG, Rockstroh B. Slow potentials of the cerebral cortex and behavior. Physiol Rev 1990;70:1–41.

Cowen MA. The brain as generator of transcephalically measured direct-current potentials. Psychophysiol 1974;11:321–35.

Cui RQ, Huter D, Egkher A, Lang W, Lindinger G, Deecke L. High resolution DC-EEG mapping of the Bereitschaftspotential preceding simple or complex bimanual sequential finger movement. Exp Brain Res 2000;134:49–57.

Eggins BR. Skin contact electrodes for medical applications. Analyst 1993; 118:439–42.

Fernandez M, Pallas-Areny R. Ag–AgCl electrode noise in high-resolution ECG measurements. Biomed Instrum Technol 2000;34:125–30.

Geddes LA, Baker LE. Principles of applied biomedical instrumentation. New York: Wiley; 1968.

Geddes LA, Roeder R. Measurement of the direct-current (Faradic) resistance of the electrode–electrolyte interface for commonly used electrode materials. Ann Biomed Eng 2001;29:181–6.

Hinterberger T, Kubler A, Kaiser J, Neumann N, Birbaumer N. A brain–computer interface (BCI) for the locked-in: comparison of different EEG classifications for the thought translation device. Clin Neurophysiol 2003;114:416–25.

Huigen E, Peper E, Grimbergen CA. Investigation into the origin of the noise of surface electrodes. Med Biol Eng Comput 2002;40:332–8.

Ikeda A, Taki W, Kunieda T, Terada K, Mikuni N, Nagamine T, Yazawa S, Ohara S, Hori T, Kaji R, Kimura J, Shibasaki H. Focal ictal direct current shifts in human epilepsy as studied by subdural and scalp recording. Brain 1999;122:827–38.

Lagerlund TD, Gross RA. DC-EEG recording: a paradigm shift in seizure localization? Neurology 2003;60:1062–3.

Marshall L, Mölle M, Schreiber H, Fehm HL, Born J. Scalp recorded direct current potential shifts associated with the transition to sleep in man. Electroenceph Clin Neurophysiol 1994;91:346–52.

Marshall L, Molle M, Fehm HL, Born J. Scalp recorded direct current brain potentials during human sleep. Eur J Neurosci 1998;10:1167–78.

Onaral B, Sun HH, Schwan HP. Electrical properties of Bioelectrodes. IEEE Trans Biomed Eng 1984;12:827–32.

Picton TW, Hillyard SA. Cephalic skin potentials in electroencephalography. Electroenceph Clin Neurophysiol 1972;33:419–24.

Tam HW, Webster JG. Minimizing electrode motion artifact by skin abrasion. IEEE Trans Biomed Eng 1977;24:134–9.

Trimmel M, Groll-Knapp E, Haider M. Different storage methods for biopotential skin electrodes (sintermetallic Ag/AgCl) and their influence on the bias potential. Eur J Appl Physiol 1982;50: 105–16.

Trimmel M, Strassler F, Knerer K. Brain DC potential changes of computerized tasks and paper/pencil tasks. Int J Psychophysiol 2001; 40:187–94.

Vanhatalo S, Tallgren P, Andersson S, Sainio K, Voipio J, Kaila K. DC-EEG unmasks very slow activity patterns during quiet sleep in preterm infants. Clin Neurophysiol 2002;113:1822–5.

Vanhatalo S, Holmes MD, Tallgren P, Voipio J, Kaila K, Miller JW. Very slow EEG responses lateralize temporal lobe seizures: an evaluation of non-invasive DC-EEG. Neurology 2003a;60:1098–102.

Vanhatalo S, Tallgren P, Becker C, Holmes MD, Miller JW, Kaila K, Voipio J. Scalp-recorded slow EEG responses generated in response to hemodynamic changes in the human brain. Clin Neurophysiol 2003b; 114:1744–54.

Vanhatalo S, Voipio J, Kaila K, Infraslow EEG. Infraslow EEG activity. In: Niedermeyer E, Lopes da Silva F, editors. Electroencephalography: basic principles, clinical applications, and related fields. fifth ed.. Baltimore-Munich: Williams and Wilkins; 2004 [in press].

Vanhatalo S, Palva JM, Holmes MD, Miller JW, Voipio J, Kaila K. Infraslow oscillations modulate excitability and interictal epileptic activity in the human cortex during sleep. Proc Natl Acad Sci USA 2004b;101(14):5053–7.

Voipio J, Tallgren P, Heinonen E, Vanhatalo S, Kaila K. Ultraslow DC shifts in the human EEG: evidence for a non-neuronal generator. J Neurophysiol 2003;89:2208–14.