



Clinical Neuroscience

New disposable forehead electrode set with excellent signal quality and imaging compatibility

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HIGHLIGHTS

- ▶ We developed a disposable forehead EEG electrode set.
- ▶ The application of this electrode set is simple and fast and does not require specialist level neurophysiological expertise.
- ▶ The measured noise levels of this electrode set are lower than those of the tested commercial disposable electrodes.
- ▶ The developed EEG set was demonstrated to be MRI and CT compatible and to lack any signs of imaging artefacts or heat induction.

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ABSTRACT

The use of emergency electroencephalography (EEG) in clinical practice is limited in part due to the lack of commercially available EEG monitoring sets that are suitable for rapid and simple use. The aim of this study was to develop a rapid and simple-to-use disposable forehead EEG electrode set for routine use that is also suitable for long-term monitoring. The EEG set we developed consists of 12 hydrogel-coated electrodes (10 recording electrodes, plus a reference and ground electrode) attached to a solid polymer film. The developed EEG set was compared to the full conventional 10–20 electrode setup in terms of the ability to detect epileptiform abnormalities in two critically ill patients. The technical quality of the EEG signal from the newly developed electrode set was excellent, and status epilepticus was reliably detected with this EEG set.

Electric performance testing showed that the impedance spectra of the developed EEG electrodes were comparable to those of three commercially available, disposable electrodes, and the noise level was lower than that of the commercial electrodes. The developed EEG set is also MRI and CT compatible and lacks any signs of imaging artefacts or heat induction. These promising results provide a reason to expect that the developed EEG set may be applicable to situations in which the full, conventional 10–20 electrode setup is not available.

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1. Introduction

Despite recent advancements in brain imaging technology such as functional magnetic resonance imaging (fMRI), positron emission topography (PET) and magnetoencephalography (MEG), electrophysiological techniques still continue to play an important role in functional imaging of the brain. Electroencephalography

(EEG) has been clinically utilised for more than 50 years and is still the method of choice for revealing electrical abnormalities in epileptic patients (Noachtar and Rémi, 2009; Praline et al., 2007). The role of EEG is crucial in patients with unexplained states of confusion or altered consciousness. EEG's diagnostic power lies in its ability to diagnose and display epileptic activity in the brain that cannot be observed with any other commonly used imaging modality.

While the electrocardiogram (ECG) is a standard technique in emergency medicine, EEG monitoring is rarely applied due to the lack of suitable instrumentation sets in emergency medical environments such as ambulances, life-saving helicopters and emergency rooms. EEG instrumentation and trained personnel are

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not readily available in the emergency department, and the diagnoses of diseases such as status epilepticus by a specialist may be delayed for hours or even days (Jordan and Schneider, 2009; Quigg et al., 2001). However, if it was possible to record EEG as soon as possible, even at emergency sites, then several neurological disorders could be promptly detected, especially status epilepticus. This would be important because these patients frequently suffer from long delays before they are referred to an appropriate medical care unit for treatment (Jordan and Schneider, 2009; Khan et al., 2005; Praline et al., 2007; Privitera and Strawsburg, 1994).

In clinical practice, scalp-EEG is typically measured using the standard international 10–20 electrode placement set in which 21 cup electrodes, commonly made of tin, gold, silver, silver-silver chloride or platinum, are attached to the scalp at precise locations to record the potential differences. However, this traditional 10–20 montage suffers from several shortcomings. First, it is relatively slow to set up and requires special skills to find the correct electrode positions and to create good skin contact, especially through the hair. Secondly, conventional EEG electrodes are not usually MRI compatible. They can cause artefacts in MRI images and the alternating magnetic field can cause tissue heating or electrode (wire) movement. Thirdly, solid metal cup electrodes do not conform properly to the skin, which causes motion artefacts in the EEG signal.

Due to the low conductivity of skull tissue, the amplitudes of the measured EEG signals are typically only 10–100 μ V (Niedermeyer, 2005). Therefore, one of the most important characteristics of an EEG electrode is low electrode–skin–electrode impedance (ESEL). Conventional metallic electrodes require skin abrasion and the use of electrolytic gel to reduce the thickness of the electrically insulating outer skin layer (i.e., the stratum corneum) and to improve the conductivity of the electrode–skin interface. Both preparation techniques subsequently decrease ESEL. However, these preparations are time-consuming, especially in terms of application and stabilisation times, and may cause discomfort to the patient. Hence, recent research into eliminating the need for these preparations has led to several new approaches, including micromachined spiked electrodes (Griss et al., 2001, 2002; Ng et al., 2009), active electrode concepts (Alizadeh-Taheri et al., 1996; Fonseca et al., 2007), carbon nanotube-based electrodes (Ruffini et al., 2008), polymer foam electrodes (Lin et al., 2011) and hydrogel-based electrodes (Alba et al., 2010; Kleffner-Canucci et al., 2012).

The aim of this study was to develop a novel rapid and simple-to-use electrode set suitable for emergency EEG monitoring. To clarify the potential of the developed EEG set, a wide variety of electric performance tests, including DC offset voltage, impedance spectroscopy and noise measurements were conducted for electrodes connected either face-to-face or to the skin. For comparison purposes, the corresponding tests were also conducted on three types of commercial disposable electrodes: Neuroline 726 (Ambu A/S, Ballerup, Denmark), Neuroline 700 (Ambu A/S) and Blue Sensor SU (Ambu A/S). MRI and CT images of phantoms with the developed EEG electrodes attached were evaluated for possible safety issues and artefacts. Finally, the performance of the developed EEG electrode set was evaluated with EEG recordings from patients in the Kuopio University Hospital.

2. Materials and methods

2.1. Electrode fabrication

A rapid and simple-to-use forehead EEG electrode set was developed into a fully functional solution over a 2-year trial period during which several technical issues, such as material selection and sensor layout, were optimised. Electrode development was

conducted in close cooperation with several specialists in clinical neurophysiology, and signal quality was evaluated with the help of a few healthy volunteers.

The electrode set is made of non-ferromagnetic and biocompatible materials. The set consists of ten recording electrodes, a ground electrode and a reference electrode attached to a solid, flexible polyester carrier film (Fig. 1). The electrodes were constructed by attaching a pure silver wire (Ag 99.9%, Ø: 0.4 mm) to clinically used wires (Ambu A/S) terminating in female 1.5 mm touch proof connectors. The ends of the silver wires were spiral-shaped and were covered with round-shaped pieces of hydrogel membrane (AG602, Amgel® Technologies, Axelgaard Manufacturing Co. Ltd., Fallbrook, CA, USA) that were 18 mm in diameter to enable the skin–electrode contact. This membrane contains ions that enhance the flow of charge across the interface. Although the membrane is sticky and adheres tightly to the skin, the attachment was sometimes ensured with Omnifix medical grade tape (Hartmann Inc., Rock Hill, SC, USA).

2.2. Electric performance testing of electrodes

The electrical performance of the electrodes was determined using several experiments following the guidelines of the American National Standards Institute and Association for the Advancement of Medical Instrumentation (ANSI/AAMI) EC-12:2000 standard for disposable ECG electrodes because no standard for the electrical testing of EEG electrodes has been published. However, some experiments, such as the AC impedance measurements, were performed more comprehensively by conducting the measurements over a wide frequency band (0.1 Hz to 100 kHz) instead of at a fixed frequency (10 Hz) as stated in the standard. Three commercially available disposable silver–silver chloride (Ag/AgCl) electrodes were also characterised for comparison purposes. The electrodes were a single-patient cup electrode (Neuroline 726, Ambu A/S), a self-adhesive solid gel surface electrode (Neuroline 700, Ambu A/S) and a wet gel ECG electrode (Blue Sensor SU, Ambu A/S). A Solartron 1260 impedance/gain-phase analyser coupled to a Solartron 1287 electrochemical interface (Solartron Analytical, Farnborough, UK) was used in the measurements. At least three electrode pairs per electrode type were tested. Data acquisition and data analysis were performed with the CorrWare, CorrView, ZPlot and ZView (Scribner Associates Inc., Southern Pines, NC, USA) software packages.

2.2.1. DC offset voltage

The DC offset voltages from pairs of electrodes attached either face-to-face or applied to the left forearm with a space of 1 cm were recorded. The forearm was selected due to its accessibility and ease of long-term measurements in accordance with several previous studies in which the electrical properties of EEG electrodes have been investigated (Alba et al., 2010; Stjerna et al., 2010). The potential difference of the electrode pair was measured for 5 min starting immediately after the application of the electrodes. Prior to attachment of the electrodes to the skin, each electrode placement site was gently swiped with an alcohol-soaked cotton pad. When Ag/AgCl cup electrodes (Neuroline 726, Ambu A/S) were tested, OL electrode paste (Berner Ltd., Helsinki, Finland) was applied between the electrodes or between the electrode and the skin.

2.2.2. Impedance spectroscopy

Electrochemical impedance spectroscopy (EIS) was used to evaluate the capability of the electrodes to transfer signals across electrode–electrolyte and electrolyte–skin interfaces. The impedance measurements were carried out in the 0.1 Hz to 10 kHz frequency band by applying a sinusoidal current of 50 μ A without any DC offset. The measurements were performed after a

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