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A novel hydrogel electrolyte extender for rapid application of EEG sensors and extended recordings

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Abstract

Objective—Dense-array EEG recordings are now commonplace in research and gaining acceptance in clinical settings. Application of many sensors with traditional electrolytes is time consuming. Saline electrolytes can be used to minimize application time but recording duration is limited due to evaporation. In the present study, we evaluate a NIPAm (N-isopropyl acrylamide:acrylic acid) base electrolyte extender for use with saline electrolytes.

Methods—Sensor-scalp impedances and EEG data quality acquired with the electrolyte extender are compared with those obtained for saline and an EEG electrolyte commonly used in clinical exams (Elefix).

Results—The results show that when used in conjunction with saline, electrode-scalp impedances and data across the EEG spectrum are comparable with those obtained using Elefix EEG paste.

Conclusions—When used in conjunction with saline, the electrolyte extender permits rapid application of dense-sensor arrays and stable, high-quality EEG data to be obtained for at least 4.5 h.

Significance—This is an enabling technology that will make benefits of dense-array EEG recordings practical for clinical applications.

Keywords

Dense-array EEG; Electrolyte; Data quality; Impedance

1. Introduction

The development of dense-array electroencephalography (dEEG) technology (128-channels or greater) over the past 20 years has elevated EEG technology to a neuroimaging technology that not only provides highly resolved temporal information of brain function but also precise localization information (Michel et al., 2004). This development has advanced understanding of basic as well as pathophysiological brain functions (Lantz et al., 2003; Michel et al., 2004; Tucker et al., 2007). Dense-array EEG studies can be accomplished with standard EEG techniques, such as standard electrodes (e.g., Gevins et al., 1997). However,

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the procedure is time-consuming and not practical for routine use, mainly due to the fact that preparation must be performed one electrode at a time.

Enabling dEEG technologies includes high-input impedance amplifiers (Ferree et al., 2001) for use with high electrode-scalp impedance recordings and rapid, dense-array sensor application methods using saline as an electrolyte (Tucker, 1993). The use of saline as an electrolyte that can be rapidly absorbed into sponge- wrapped Ag/AgCl electrodes (Tucker, 1993) permits dEEG sensor arrays to be applied in ~15 min. However, the limitation of this method is that scalp-electrode impedances rise due to electrolyte evaporation such that good EEG data are only obtainable for ~90–120 min (depending on relative humidity) without re-wetting of the electrodes, even for high-input impedance amplifiers.

EEG electrolytes come in either water-based (i.e., gel) or polyethylene glycol (PEG)-lipid-based (i.e., cream or paste) forms. The PEG-lipid based electrolytes usually contain very little water content. Both types of electrolytes are effective because they overcome the poorly conductive stratum corneum layer by hydration and filling the ducts of the skin with electrolyte. This process changes the stratum corneum into a highly ion-conductive layer and can reduce electrode-skin impedance down to 50 kΩ without abrasion (Ferree et al., 2001). Although skin abrasion, to bypass the stratum corneum, can be performed to further reduce electrodeskin impedance, it is not necessary given that modern, high-input impedance amplifiers can compensate for the high electrode-skin impedances without signal loss or significant increase in noise (Ferree et al., 2001; Kappenman and Luck, 2010). Electrode-skin impedances for gel electrolytes generally are lower than those observed with PEG-lipid electrolytes immediately after application because they contain water and can easily hydrate the stratum corneum. A drawback of water-based electrolytes is that recording duration is limited because of evaporation, requiring maintenance for long-term recordings. However, it is noted that even gel electrolytes have longer recording durations than saline electrolytes. PEG-lipid electrolytes, due to their composition, are very effective for long-term recordings (e.g., Falco et al., 2005).

A hydrogel is a three-dimensional network of polymer chains that can absorb water in large quantities. It is the presence of this three-dimensional network that produces a semi-solid mass as opposed to a simple polymer solution. Other gels that contain thickeners, such as lipids or PEG do not form such networks. Depending upon the polymer used, hydrogels can also be designed to have stimulus (such as temperature) responsive and adhesive properties.

In this paper, we evaluate the performance of a novel hydrogel as an electrolyte extender. This hydrogel consists of a NIPAm (N-isopropyl acrylamide:acrylic acid) co-polymer that has a phasetransition temperature of approximately 35 °C. That is, the hydrogel is capable of changing its thickness or colloidal properties upon application to the skin by extrusion of water at skin temperature. As it loses water it becomes more adhesive. This phase-change property is inherent to the hydrogel and determined during formulation of the hydrogel itself and is not controlled during application.

Although DBH can serve as an electrolyte in a similar manner as gel, cream, or paste electrolytes, in the present study we examined its usefulness for extending the recording duration of EEG sensors that use saline as an electrolyte (Tucker, 1993). As previously described, a benefit of using saline as an electrolyte is that loading of electrolytes into EEG electrodes can be accomplished simultaneously to enable rapid application of dense sensor arrays.

2. Materials and methods

2.1. Participants

A total of three participants were included in the study. The average age of the participants is 23 (SD = 1.7). Participants volunteered for the study and were compensated $10 per hour of their time. All participants provided informed consent prior to participation in this study. The study protocol was approved by the Institutional Review Board at Electrical Geodesics Inc. Because hair type is an important factor determining the contact between the electrode and scalp and because hair wicks moisture from the sponge-wrapped electrodes and therefore increases evaporation rate, the three participants had varying hair lengths (short, shoulder-length, and back-length).

2.2. Materials

Saline—This electrolyte is simply a mixture of potassium chloride (KCl) with water (Electrical Geodesics, Inc. Eugene, OR).

Saline–DBH—Twenty-five mL of DBH (at 7.5% gel concentration) was manually mixed with 250 mL of KCl–saline solution. DBH has passed cytotoxicity, sensitization, and irritation tests.

Elefix (Nihon Kohden, Tokyo, Japan)—This is a PEG-lipid-based electrolyte. It is mainly composed of propylene glycol, glycerin, and petrolatum. It was used as the reference electrolyte because it is often used for long-term EEG recordings in clinical settings.

2.3. EEG recordings

The EEG was acquired using a 256-channel HydroCel Geodesic Sensor Net (HCGSN, Electrical Geodesics, Inc., Eugene, OR). Recordings were referenced to Cz. The EEG was lowpass filtered (100 Hz) prior to being sampled at 250 s/s with a 22-bit analog-to-digital converter. The data were acquired from all participants in three different recording conditions (saline, saline–DBH, and Elefix). Each recording session occurred on different days.

For saline and saline–DBH sessions, each sensor of the HCGSN is wrapped in a sponge and the entire net was soaked in the electrolyte prior to application. Elefix was individually applied to the cavity of each sensor of the HCGSN after application of the sensor net. Like all applications of the HCGSN, care was taken to ensure that all sensors were not sitting on hair but were in contact with the scalp.

Immediately after all sensors were seated on the scalp, electrode-scalp (resistive) impedances were measured to ensure that all electrode-scalp impedances were below 100 kΩ. For impedance measurement, all channels were set at a fixed voltage, after which 20% of the channels were turned off. Those that were turned off were widely and evenly spaced as possible such that each off-sensor is, at a minimum, fully surrounded by a ring of emitters. Impedance was then quantified as:

$$\mathrm{Impedance}=\frac{10.0\times \mathrm{IdealAmplitude}}{\mathrm{MiddleAmplitude}}-10.0$$

IdealAmplitude is the mean channel amplitude without an external impedance, which is calculated by injecting a calibration signal for each channel, then measuring the amplitude for each channel, after which mean amplitudes over all the channels are derived.

MiddleAmplitude is the amplitude of the signal recovered from the measurement (i.e., center) channel.

After this initial impedance measurement no retouching or fixing of electrodes was performed. Once all electrode-scalp impedances were below 100 kΩ, an elastic, cotton cap (MT Spandage, Medi-Tech International Corporation, Brooklyn, NY) was applied on top of the HCGSN to reduce the likelihood of disruption of the electrode-scalp contact.

Recording of resting EEG occurred in a sitting position with lights off and alternated between eyes open and eyes closed. Recordings were at approximately 1-h time intervals. Each session lasted between 2 and 4.5 h, depending on electrolyte. In between recordings, participants were free to move about in the laboratory and work on computer workstations.

3. Results

Because electrolyte evaporation is facilitated by the moisture wicking property of hair and because we want to examine the ability of DBH to extend EEG recordings, analysis of the data were performed only on data acquired over regions with hair. On a 256- channel HCGSN, a total of 164 channels are positioned over hairy sites.

3.1. Electrode-scalp impedances

We examined the median electrode-scalp impedances of the 164 channels over four time intervals for the saline electrolyte and five intervals for the saline–DBH and Elefix electrolytes. The saline recording was limited to 3 h because saline, as an electrolyte, lasts approximately 1.5–2 h. The recording at 3 h is to confirm the lack of EEG quality. The data were submitted to a repeated-measures ANOVA with Electrolyte (saline, saline–DBH, and Elefix) and Time (four levels) as factors.

Fig. 1 shows the median impedance level at each time interval for the three electrolytes. The analysis revealed significant main effects for Electrolyte and Time. These were qualified by a significant trend for the interaction between Electrolyte and Time, $F(6,12) = 13.4$, $p < .06$ (Huynh–Feldt corrected). This effect showed that impedances for saline electrolyte rapidly increased over time. By 1.5–2 h, the impedances for saline are quite high and are associated with poor EEG quality (see below).

Impedances for the saline–DBH condition increased at a slower rate. At the 2.5–3 h interval the average median impedance value across the three subjects is 62 kΩ, which is very similar to the average median impedance value for Elefix, 50 kΩ. As can be seen in Fig. 1, the initial impedance associated with Elefix is higher than the other two electrolytes and decreases over time. This is because both saline and saline–DBH electrolytes rapidly hydrate the scalp. In contrast, ions from Elefix take much longer to diffuse into the stratum corneum.

At 4–4.5 h, impedances associated with the saline–DBH electrolyte continue to rise, 84 kΩ, while impedances for Elefix continue to decrease, 42 kΩ. However, even at 84 kΩ, quality EEG can be acquired with modern high-input impedance amplifiers (see Section 3.2).

3.2. EEG quality

The EEG was high-pass filtered (1 Hz) and a ten-second segment of eyes-closed, artifact-free EEG was extracted at each time interval for all 164 channels. The data were spectrally decomposed using a fast-Fourier transform. This was done on one-second segments, resulting in a 1 Hz resolution, and averaged across 10 s for each time interval. The data were then averaged across all 164 channels and summed into the following frequency bands: delta (1–4 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (12–13 Hz), 60 Hz, and gamma (13–100 Hz,

excluding 60 Hz bin). Factors included in the repeated-measures ANOVA model include Electrolyte, Time, and Frequency (six levels).

The analysis revealed significant main effects for electrolyte, time, and frequency. These main effects were qualified by significant two-way interactions involving electrolyte and time, electrolyte and frequency, and time and frequency, which were all in turn qualified by a significant 3-way interaction involving all three factors, $F(30,60) = 5.88$, $p < .03$ (Huynh–Feldt corrected). To examine this 3-way interaction, separate repeated-measures ANOVAs were performed on the three electrolyte data sets. Results for saline electrolyte revealed a significant two-way interaction involving Time and Frequency, $F(15,30) = 8.64$, $p < .05$ (Huynh–Feldt corrected). This interaction showed that as recording time increases, energy in the low frequency range (delta and theta) increases significantly, particularly between the first and second hours (see Fig. 2).

Results for the saline–DBH electrolyte did not reveal any significant effects. On the other hand, results for the Elefix electrolyte set revealed a significant main effect for frequency, $F(15,30) = 17.46$, $p < .01$ (Huynh–Feldt corrected, see Fig. 2). To compare the saline–DBH data against Elefix data, we performed an analysis with electrolyte (saline–DBH, Elefix), frequency, and time as factors. The analysis confirmed that there was no difference between the Elefix and saline–DBH data in any of the frequencies over time. In other words, the data acquired with Elefix and saline–DBH are equivalent (see Fig. 2).

In this next analysis, we examined the performance of saline–DBH for longer term recordings because we also acquired data with saline–DBH and Elefix at 4–4.5 h post application. Factors included in the repeated-measures ANOVA model include Electrolyte (saline–DBH, and Elefix), time (five levels), and Frequency (six levels). The results did not reveal any significant effects, confirming that the EEG acquired with Elefix and saline–DBH are equivalent for recording durations up to 4.5 h (see Fig. 3). Fig. 4 illustrates the EEG acquired with saline–DBH and Elefix electrolytes for one channel at the 4–4.5 interval.

4. Discussion

In this paper we evaluated the performance of a novel hydrogel to act as a saline electrolyte extender. The benefit of using saline as an electrolyte is that, with an appropriate electrode technology, it permits rapid application of many EEG electrodes and immediately reduces the electrode-skin impedance to permit high-quality EEG recordings. With the cup design of each sensor on the HCGSN, those sensors that lay on bare skin are effectively sealed such that very little electrolyte evaporation occurs, and EEG recordings with a saline electrolyte can be performed over many (5–8) hours with good signal quality. However, those scalp sensors that sit over hairy regions of the scalp dry quickly because (1) a tight seal cannot be formed due to the presence of hair and (2) hair wicks moisture away from the sponges.

We showed that when DBH is added to the saline electrolyte, the electrode-scalp impedance is immediately reduced without the need for scalp abrasion. Over time, electrode-scalp impedance rise rapidly for the saline electrolyte. In contrast, the electrode-scalp impedance associated with saline–DBH slowly rises and is well under 100 kΩ, even after 4.5 h. On the other hand, without scalp abrasion, electrode-scalp impedances associated with Elefix continue to decrease and stabilize at approximately 50 kΩ.

Evaporation of saline in the saline–DBH formulation leaves a dry polymer crust that effectively acts as a barrier to reduce the evaporation rate of the saline-filled, sponge-wrapped electrode. Moreover, DBH has adhesive properties at high polymer-to-water ratios (as that used in the present study) such that evaporation results in the sponge surface adhering to the skin. In turn, this improves the interface with the hydrated epidermis.

Evaporation of saline will continue such that quality EEG will not be obtainable, however, even with DBH. On short hair, electrodes can make good contact with the scalp and an effective evaporation barrier can be established with DBH's dry polymer crust. We have informally observed that with short hair participants, quality EEG can be obtained for up to 8 h without electrode maintenance. In the present study we included participants with different hair lengths, and, indeed, the electrode-scalp impedances increased at the fastest rate for the participant with the longest hair and slowest for the one with shortest hair. We are currently performing studies to evaluate maximal recording time as a function of hair length.

The EEG data acquired immediately and 1-h post application are comparable between the three electrolytes (see Fig. 2). For saline electrolyte, at 1.5–2 h post application, the EEG is still acceptable but there is an increase in energy at low frequencies (delta and theta). EEG acquired with saline–DBH and Elefix are comparable throughout the recording during duration of the study (see Figs. 2–4). Previous studies have shown that long-term EEG acquired with paste-like EEG electrolyte (such as EC2, Grass- Telefactor) is of better quality than those obtained with a gel electrolyte and collodion combination (Falco et al., 2005).

In conclusion, saline–DBH is a technology that enables rapid application of dEEG sensor arrays for stable EEG recordings up to 4.5 h in subjects with varying hair lengths. Quality of the EEG data is comparable to existing methodologies. Future studies will have to examine the maximal recording duration of saline–DBH as a function of hair length.

Acknowledgments

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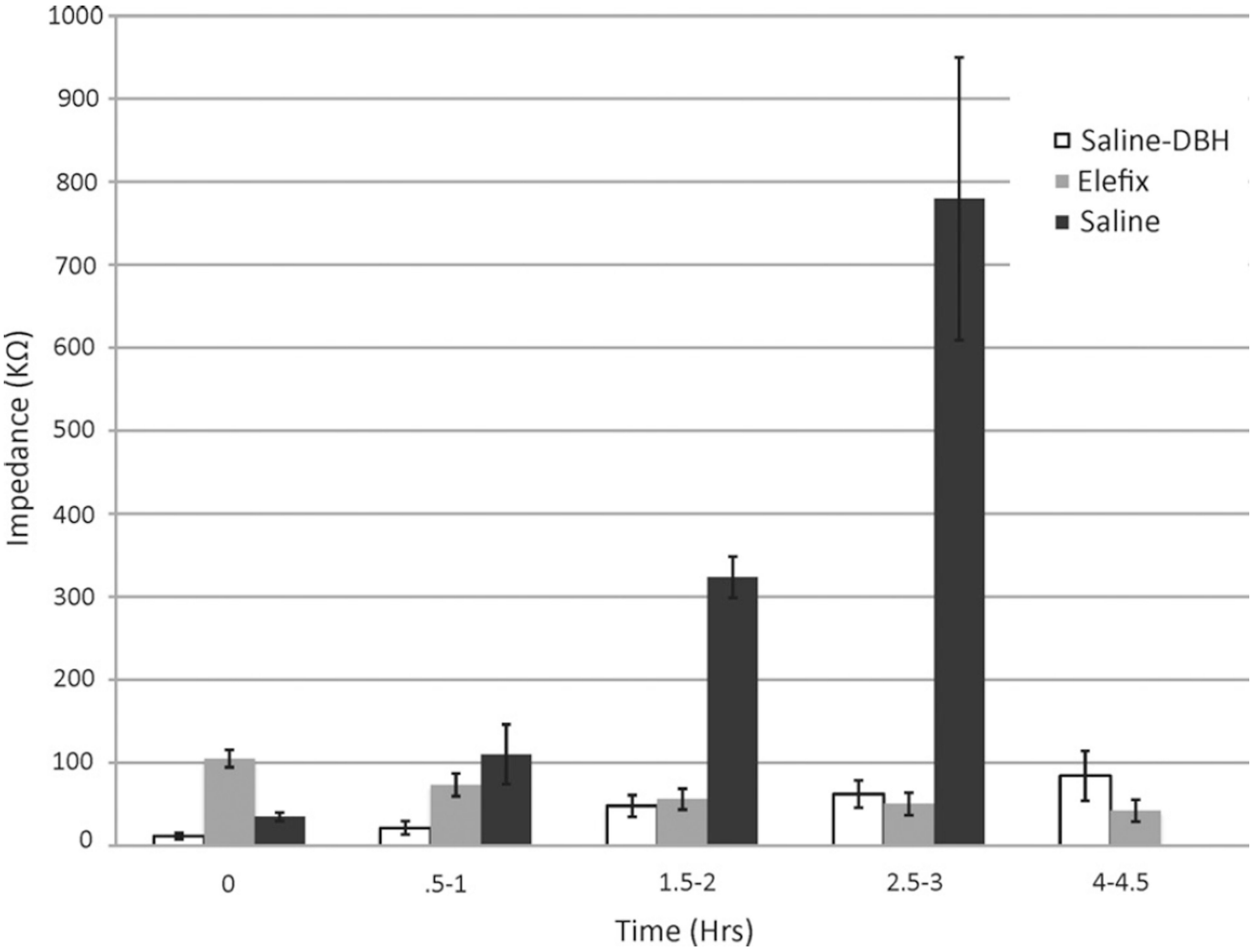

Figure 1.
Median electrode-scalp impedance as a function of electrolyte and time.

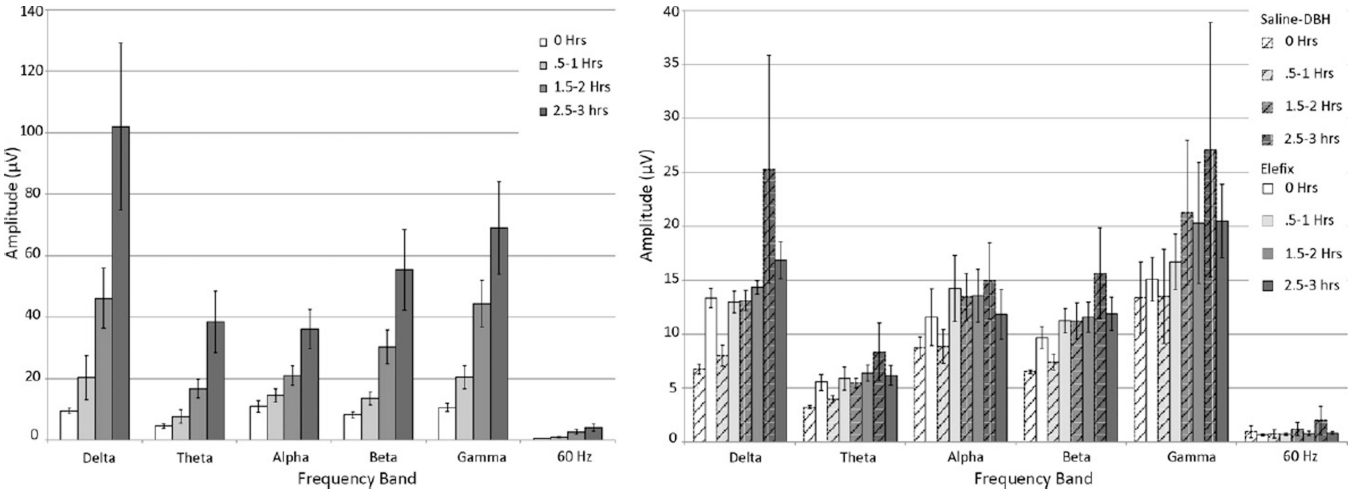

Figure 2.

EEG amplitude spectra as a function of electrolyte and time. Left: saline electrolyte; right: saline–DBH and Elefix.

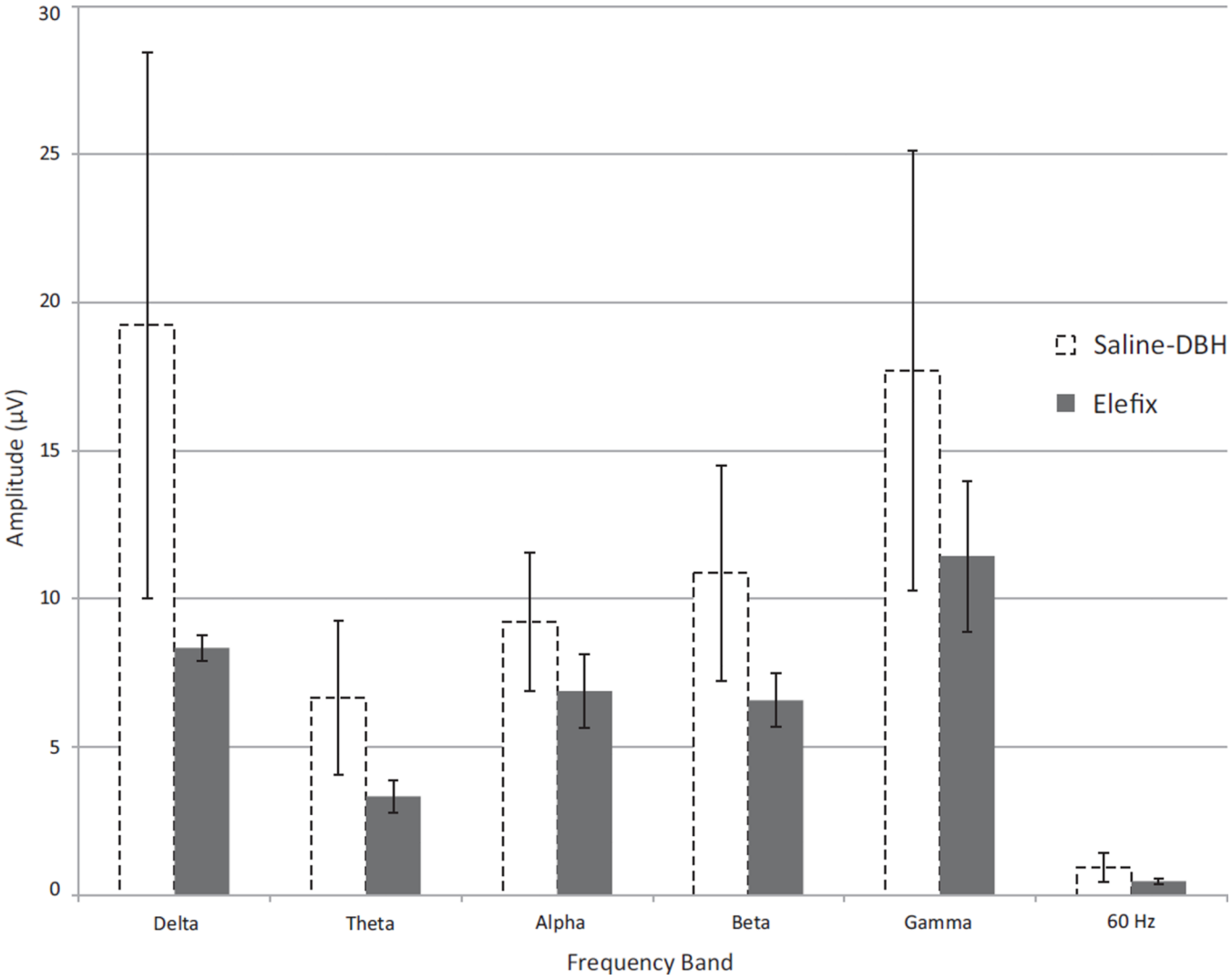

Figure 3.
EEG amplitude spectra for saline–DBH and Elefix electrolytes at 4–4.5 h post application.

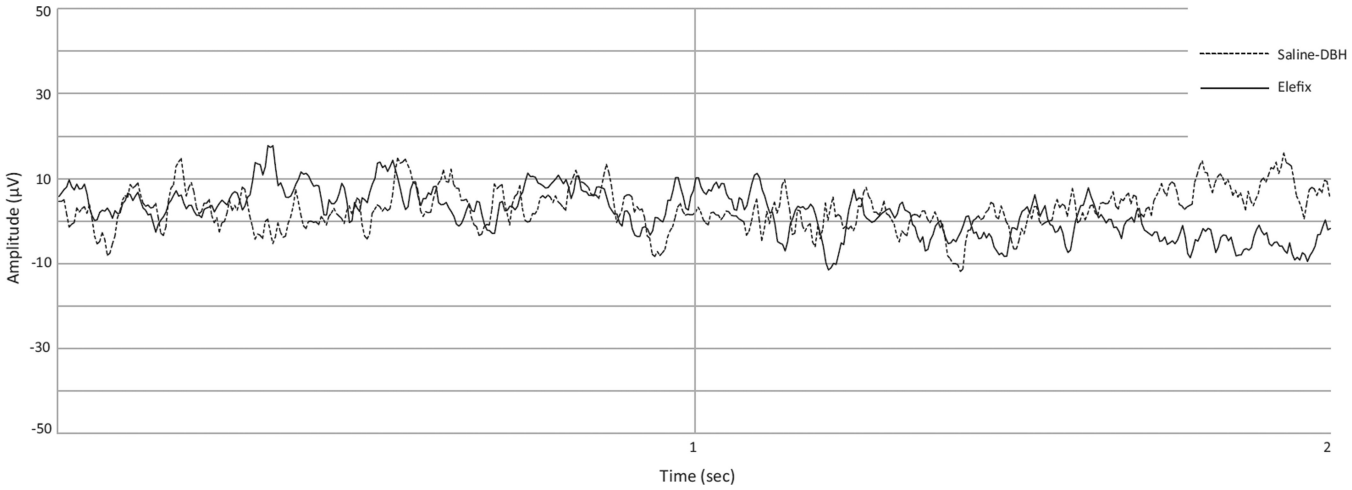

Figure 4.
Sample EEG for one electrode at 4–4.5 h post-application time interval for saline–DBH and Elefix electrolytes.