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"The best way to be boring is to leave nothing out."

Voltaire

DC-stable electrode-skin interface for human EEG recordings

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Abstract – A pre-requisite for a direct current (DC) stable electrode-subcutaneous tissue interface is that the transdermal epithelial potential (TEP) is short circuited (i.e. zero) to eliminate skin originated signals.
In this study six different methods were compared to obtain this goal. Skin scratching with a hypodermic needle served as a reference method (the results of this method were also verified) and it was compared against five different methods utilizing 3 prick needles and a self-developed mini-puncturing method enabling a depth controlled puncturing. Skin short circuit was assessed by recording TEP immediately after the operation as well one day later. The most reliable method for overnight recording was scratching. Puncturing methods were quick and easy to operate being practical for clinical use and most of them produced a short circuit sufficient for acute recordings. Unfortunately, the TEP of punctured skin was often partially recovered within 24 hours, and these methods had only a limited value with this time scale. Interestingly it was found that visible blood is not a guarantee of a short circuit, nor visible blood is required for the short circuit.

Introduction

The recent findings (e.g. Voipio *et al*, 2003; Vanhatalo *et al*, 2002 and 2003a,b) have risen a demand to extend the electroencephalography (EEG) bandwidth from the clinical (0.5-70 Hz) standard to cover the whole physiological frequency range (at least 0.01 Hz to 1000 Hz; Curio, 2005). A faithful recording of slow oscillations of EEG signals are possible with a DC-EEG technique, which has recently become widely accessible and suitable for routine bedside recordings (Vanhatalo *et al*, 2003b). DC-EEG recording requires a genuinely DC-coupled amplifier with a wide input range (≥ ±100 mV) and of excellent DC-parameters, as well as a DC-stable electrode-skin interface. High quality DC-coupled amplifiers and high quality non-polarizable electrodes (i.e. silver|silverchloride (Ag|AgCl); see Tallgren *et al*, 2005) are commercially available, but the practical solution to obtain DC-stable electrode-skin interface has been a challenge. The lack of the optimal method is the main hindrance for the DC-EEG technique to spread widely. However, DC-EEG is the not the only method that requires the short circuit of the skin. Transcranial magnetic stimulation is a method that induces electrical stimulation to brain by strong external magnetic pulses. EEG can be recorded during the stimulation. A properly designed EEG-amplifier recovers within milliseconds from the pulse, but intact or poorly short circuited skin may generate millivolt-scale signal spoiling the EEG data for hundreds of milliseconds (personal communication with Marko Ollikainen, MSc (EE), Nexstim Ltd, Finland).

This study was set out to develop and evaluate methods that would be clinically practical and reliable in acute and even overnight recordings. Currently, a widely used method to obtain DC stable skin-interface is obtained by scratching the skin by a hypodermic needle until the reddish subcutaneous tissue is exposed (Voipio *et al*, 2002). Unfortunately the scratching method has many drawbacks; it is slow to perform and requires some experience, it is difficult to do in hairy regions, it often leaves scratches to skin, and it may feel uncomfortable thus having a low practical value in routine clinical work. An optimal skin short-circuiting technique should be easy to perform, give equivalent results with all performers and subjects, and yet the tool should be cheap, disposable and easily accessible and/or available. The aim of the study was to find out if standard allergy prick sticks, or a “mini-puncture” tool constructed from standard clinical parts, could be used to short circuit the skin and - if not - what kind of a method should be looked for.

Origin of skin voltage

Skin forms a physiological barrier for diffusion of water and ions (Kalia *et al*, 2000) and it is charged with a relatively high transdermal potential of typically +10…-60 mV (e.g. Scheuplein, 1971 and 1978). The potential is generated by a constant ionic gradient (Thakor and Webster, 1978) and ionic potential of sweat glands (Edelberg, 1977; Martin and Venables, 1966). The relatively thin (~2…20 µm) barrier has a very high resistance (Scheuplein, 1978) but allows a good capacitive coupling of conventional EEG frequency band (>0.5 Hz) through. The temporally and spatially (Picton and Hillyard, 1972) varying skin potential (i.e. TEP) even in electrodes located only few centimetres from each other and negligible DC conductance accounts for the generation of low frequency noise and artefacts because all ionic activity is seen as voltage change. This precludes the possibility of using any signal processing for their mathematical extraction from the record (see Ille *et al*, 2002). Hence the only reliable way to exclude EEG contamination by skin-generated artefacts is by direct elimination of the TEP by opening the insulation barrier, i.e. short circuiting the TEP.

Subjects and Methods

Five male and two female volunteers (average 29 years) from our research group participated this study. Experiments were carried out from scalp (5 persons) and from inner forearm (1 person). Recordings from forearm and scalp were compared.

Recordings were performed using a custom made DC-amplifier with a fixed gain of 100, sampled at 300 Hz with 49 µV resolution. The potential of manoeuvred skin was recorded against a scratched skin by Ag|AgCl electrodes (**13** mm^2; model LP220, In Vivo Metric, Ukiah, California, USA). Electrodes were attached to a plastic holder (designed by the author) to keep the active electrode material 6 mm above the skin. The tubular space (diameter 4 mm) between electrode and skin was filled with Signagel (Parker Laboratories Inc, Fairfield, NJ, USA) electrode gel because it does not irritate scratched skin, and it contains a sufficient amount of chloride required by Ag|AgCl electrodes (see Tallgren *et al*, 2005). Electrode holders were fixed to skin by double-side adhesive collars. Schematic drawing of the recording setup (without plastic holder) is outlined in Figure 1A. Figure 1B presents an equivalent circuit of recorded voltage. In overnight recordings electrode gel was twice added (at 20h and 24h) between recording sessions.

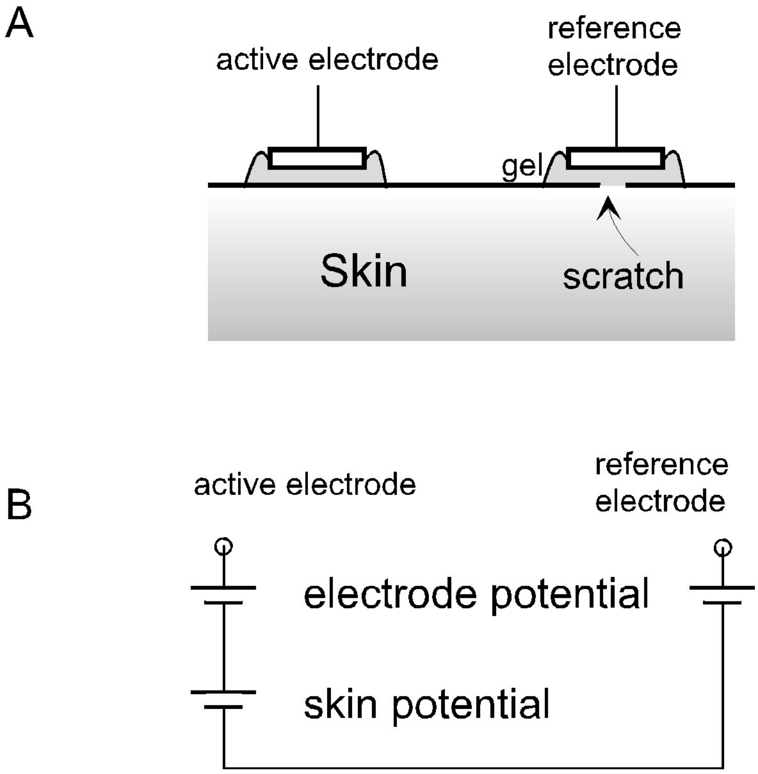

Fig 1. **A.** Recording configuration. Skin potential is recorded against a stable reference electrode attached on scratched skin. **B.** Equivalent circuit of recorded potential.

Short circuiting methods

The following five tools (Fig. 2) and six methods were evaluated: 1) hypodermic needle used for scratching (**Terumo Neulus** 26G, 0.45x12 mm, http://www.terumo-europe.com, Terumo Europe NV, Research Park Zone 2 – Haasrode, Interleuvenlaan 40, B-3001 Leuven, Belgium.), 2-3) allergy prick needles (Alk-Abello: **ALK Lancet**, www.alk-abello.com, ALK-Abelló A/S, Bøge Alle 6-8, DK-2970 Hørsholm, Denmark; and **Allersharp**; www.allersharp.com; manufactured by Riverside Medical Packaging Co, Ltd, Newmarket Drive, Derby, DE24 8SW UK for HMB Medical Concepts Ltd, Highfield House, Derby, DE22 1 HT, England.) both containing one peak, 4) allergy prick needle containing six peaks (GP-1 Greer Laboratories, Inc. P.O.Box 800 Lenoir, North Caroline 28645, USA) and 5) a self-made "mini-puncturing" tool that was constructed by inserting a hypodermic needle (the same type that was used for scratching) concentrically through a “pipe” that was cut from an 1.2 mm (diameter) hypodermic needle (gel needle can also be used) so that the sharp tip protruded 0.5 mm over the end of the outer pipe. The sealing was secured by hot melt glue. This tool was outlined together with Dr Sampsa Vanhatalo, and one such a kind of an idea is also presented by Burbank and Webster (1978).

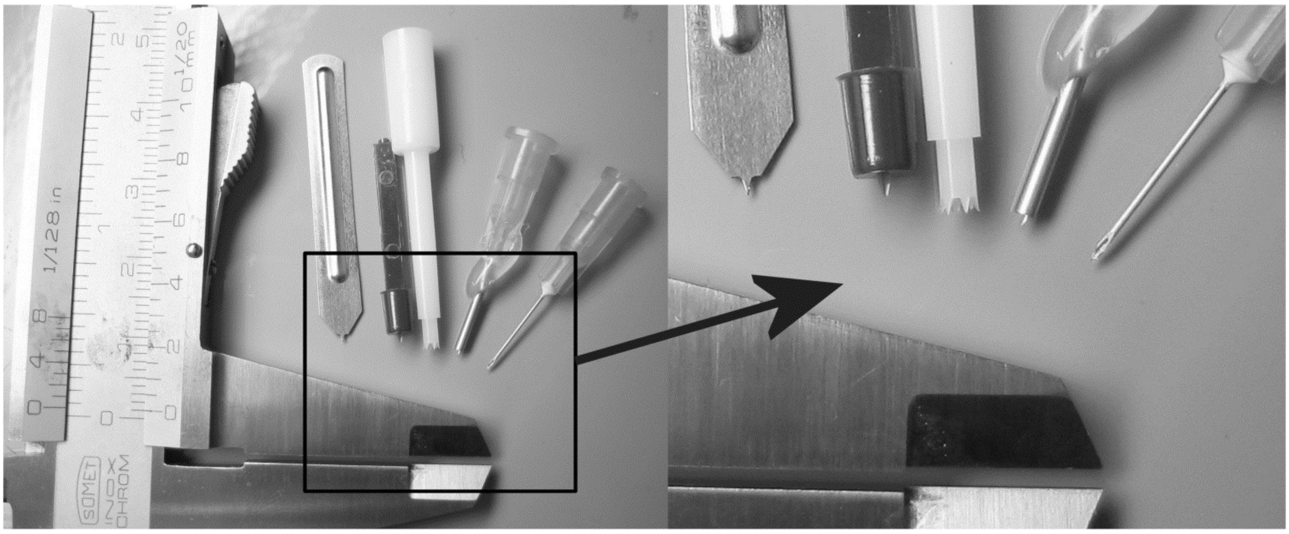

Fig 2. Tools examined. From left to right: Alk-Abello, Allersharp, Greer Lab, mini-puncture, and the needle.

Instead of skin impedance, skin potential was monitored because it directly reflects the propensity of the skin to generate artefacts. Skin conductance could also be the monitored parameter, but high quality measurement would require to use a very low frequency or DC-current, which may lead to electrode/tissue polarization and erroneous results. The location of the reference electrode was within 3…10 cm from the active electrodes in the forearm recordings, and 2…32 cm in the recordings from the scalp locations. Scalp recordings were made from non-hairy regions, i.e. from temporal deviations. Skin potential was compared against a low frequency power as suggested by Sampsa Vanhatalo.

The following skin manoeuvre methods were used: hypodermic needle was used to perform a gentle, approximately 3 mm long scratch on the skin so that a reddish tissue fluid was seen. Allersharp and Alk-Abello prick needles were decisively pressed towards the skin, resulting in a single penetration point. Prick needle of Greer laboratories was either pressed straight, or pressed and rotated (both methods are used in allergy testing), resulting in either six small penetrations or a circular incision, respectively. With the self-made mini-puncture device five strokes were performed within a circle of diameter 4 mm, resulting in five small and sharp-edged penetrations.

Results

Figure 3 presents the recording protocol. Recordings from intact skin demonstrated prominent, apparently arbitrary, slow baseline fluctuations. After collecting baseline from intact skin, skin was operated by one of the previously described method and the TEP dropped if complete or partial short circuit occurred. Later (20 minutes or 24 hours) the same electrode sites were scratched by a needle to notice if further reduction in the TEP could be achieved. At the end, the recording electrodes were taken from the skin and put against reference electrode to record the electrode offset voltage. This voltage was subtracted from all results given.

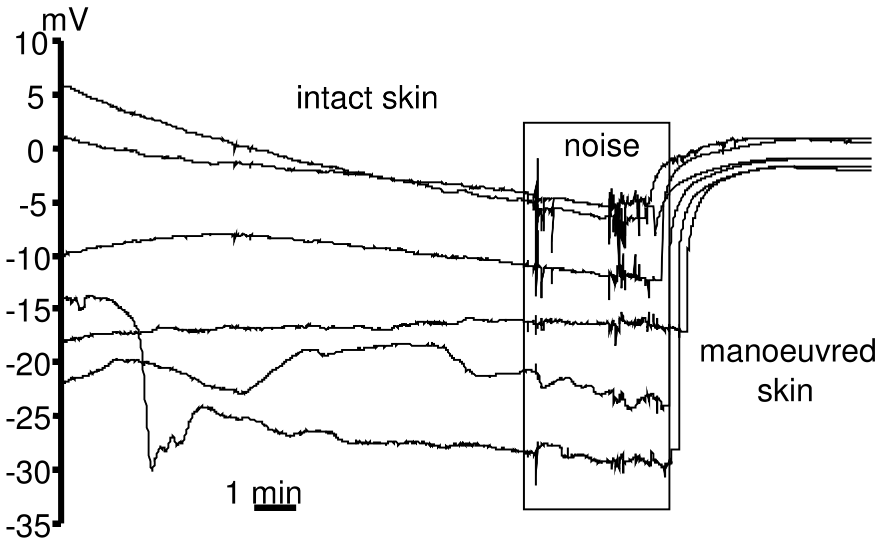

Fig 3. Recording protocol. Intact skin has a high and variable skin potential, but after the skin is manoeuvred by some of the methods (in this case Greer prick) the skin voltage drops close to zero and remains fairly stable. At the end the skin is scratched to notice if further reduce in skin potential may be achieved (not shown). After manoeuvre skinpotential is either recorded immediately (acute results) or a day later (24h results). (The traces in shaded boxed are contaminated by movement artefacts.)

For a control, the possibility that electrode detaching and reattaching would cause changes in the electrode offset potentials was excluded. The change was always less than 0.5 mV (n= 50). Neither there was an inter-electrode voltage (in arm) if the skin was scratched under both electrodes. Thus the changes in the electrode offset potentials were negligible compared to the TEP.

The results obtained from forearm and from scalp were identical, and thus pooled.

Acute effect

While all short-circuit methods resulted in some drop in the TEP, there were substantial differences between methods. The voltage indicated in Fig. 4 is from a stable level of the type of experiment in Fig 3. Each point is an individual electrode. Intact skin had a very wide distribution of voltages, even in small region.

The validation criteria of sufficient short circuit was set to TEP $\leq$ 8 mV both in acute effect and 24h (see later) results. The set criteria allows a moderate electrode potential but, according to the results shown later (see Fig. 5), the low frequency noise is low. The TEP after scratching was always very close to zero ($\leq$ 0.5 mV, N=5) compared against later performed re-scratching.

Allersharp prick stick produced sufficient short circuit in 14/17 cases. Blood was never seen. The tool is small and could be operated through electrode holders. The shaft is quite small for easy handling.

Mini-puncture method was a reliable method, the set criteria was filled in 10/11 cases.

Alk-Abello prick induced the short circuit in 8/8 cases. Blood was often seen. The tool is flat but wide and could not be operated through electrode holder.

Greer Labs' prick was a reliable method to induce the short circuit. In 11/11 cases it broke the skin barrier sufficiently and never produced bleeding. The prick was small enough to be operated through electrode holder but the shaft was large enough allowing easy handling.

Greer Labs' prick produced a short circuit with single ±180° rotation (fig 4) in 6 cases of 9. This method was the only one that did not attain a (near) stable voltage immediately, but the TEP continued to decrease with time, maybe due to gel penetration (McAdams *et al*, 1996) to partially broken skin.

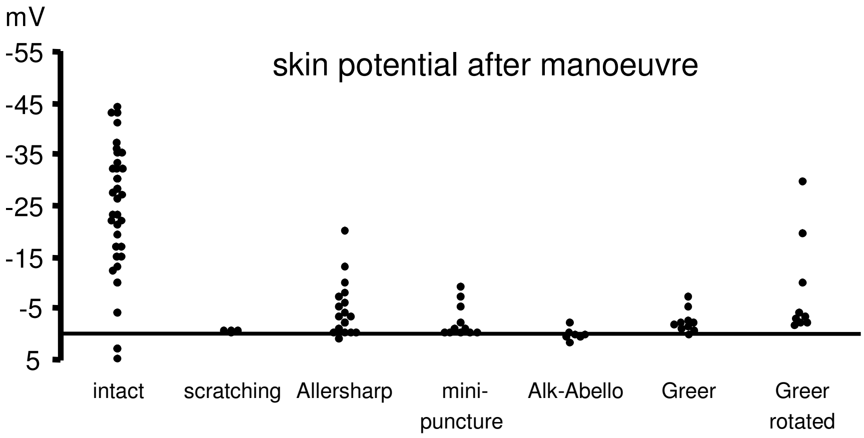

Fig 4. Skin voltage shortly (~3 min) after manoeuvres. By definition scratched skin has the TEP very close to zero.

24h results

Figure 5 presents results obtained from the same kind of experiment but the skin potential was recorded 24h later. Scratching proved to be the most reliable method to short circuit (12/12) the TEP for at least 24 hours. Re-scratching did not produce any significant change to the potential indicating a complete short circuit. Scratching method has many drawbacks, but of the tested methods it was the only one with predictable results, which means that it may be used when the most reliable method of skin manoeuvre (for e.g stable common reference electrode) is needed.

TEP short circuit obtained by Alk-Abello prick was mostly recovered within 24 hours. None of the 5 test sites remained short circuited. Short circuits obtained by Allersharp prick were mostly recovered too, only 2/6 electrode site remained short circuited. Short circuit obtained by Greer lab's prick was recovered at least partly in 6 of 10 cases. Due to incomplete initial TEP short circuit the Greer prick rotating method was not monitored for 24h. (But; see discussion). Short circuit obtained by mini-puncture method remained in 11/16 cases.

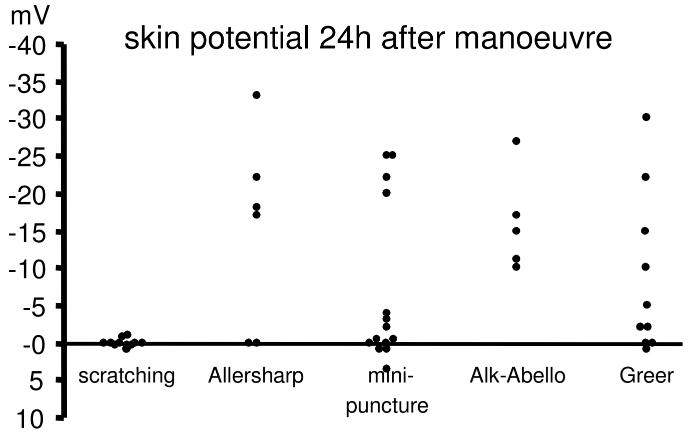

Fig 5. Skin potential 24h after manoeuvres.

Low frequency noise and TEP

Figure 6 presents the low frequency noise (0.05-0.5 Hz) against TEP. The total low frequency noise power between frequencies 0.05-0.5 Hz was calculated from 600 s long period divided to twenty 109 second long epochs. The correlation between low frequency power and the TEP was -0.62. The variance in Fig 6. reflects the fact that the skin has the potential to vary, but does not necessarily do it.

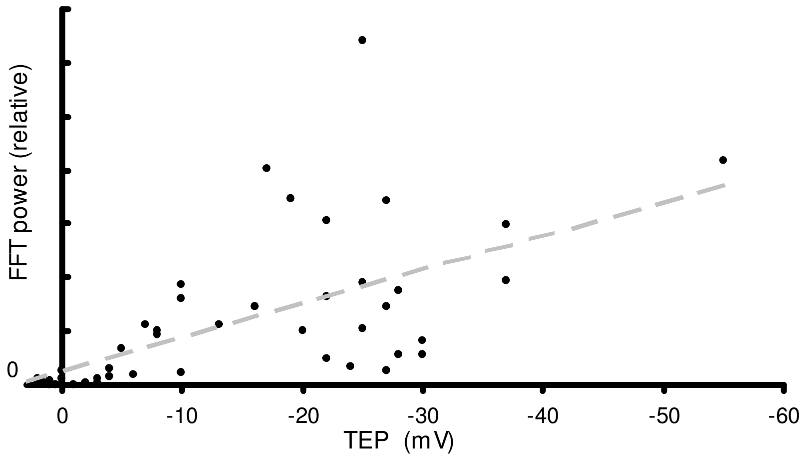

Fig 6. Low frequency power correlates strongly with the skin potential. Intensive low frequency power is associated with high skin potential. Dashed line indicates a linear fit of data.

Discussion

In this study was worked out if allergy prick sticks or easily accessible mini-puncture tools could be used to produce skin short circuit. According to the results, for acute recordings Greer labs' prick or mini-puncture method offers the best results with least discomfort. Scratching and Alk-Abello methods are not recommended due to the higher level of discomfort they induce. For extended time periods scratching by a needle offers the best results. Note however, that some 24h experiments were made when the initial short circuit had been verified. Experiments were carried out only by Greer-labs rotating method, but the results were promising. (In this particular case the ±180° rotation was required *twice* instead of a *single* ±180° rotation.) The short circuit remained in all 5/5 cases for 24h (data not shown). This indicates that if the initial short circuit is verified also the Greer labs' rotating method may (and maybe some others too) be used to obtain short circuit lasting for 24 hours. Even though the "level of discomfort" induced by different manoeuvres was not a subject of this study, subjective "order of discomfort" was as follows (most discomfort first): scratching, Alk-Abello, mini-puncture, Greer lab either rotated or pricked, Allersharp.

During this study it was found that a visible blood is not a guarantee of the complete short circuit of the TEP. The finding is intelligible, because voltage gradient exists across the thin insulating layer right below the dead cells of stratum corneum and the insulation must be removed in sufficient area – but not necessarily deeply – to short circuit the potential and to provide a low resistance pathway. This requirement makes unlikely the existence of a gentle method (i.e., attempts with special gels or gentle grinding will most likely fail) that would provide predictable results with all individuals, **unless** the skin potential is monitored during the operation.

Puncturing five times to a depth of 0.5 mm is often enough and seldom felt highly discomfortable. Unfortunately this method has some practical difficulties. If the movement of the sharp tip is not fast enough, it does not pierce the skin but the skin stretches and sidesteps the tip. A tool that would have multiple sharp tips and that could be "shooted" to avoid skin stretching would be optimal. Unfortunately, such a commercial tool does not exist. Due to the lack of a suitable tool, abrasive methods should be considered. Grinding process could be easily automated by stopping the grinding when the short circuit is obtained. It is quite easy to construct a device that performs the controlled grinding, and one such solution is presented by Zipp (1983).

The conclusion from the results is that methods utilising multiple sharp tips are the most reliable. A single penetration does not guarantee a good short circuit and the likelihood of sufficient short circuit increases with number of penetrations. Five penetrations is a good compromise.

According to this study, small punctures heal (at least partly) within a day. The fast healing process is an advantage in short term recording, but a re-operation may be needed in long-term DC-EEG recordings needed for e.g. epilepsy diagnostics. For this reason there is a need to monitor the propensity for slow artefacts, i.e. TEP. One possible method is to monitor low frequency power. In this study it was found that the low frequency power correlated strongly to the TEP. As a consequence, low frequency EEG may be seriously contaminated by skin originated signals if the TEP is large. In other words, skin short circuit **must** be **obtained** to **reliably** record slow frequency signals.

As a conclusion, scratching is the most reliable method to short circuit the TEP, while some allergy prick sticks may also be used. In most cases one should confirm the short circuit of TEP, which is easily carried out if electrode potentials are first measured. During long term recording electrode potential can not always be measured, and this study introduces a method based on monitoring of low frequency power as a tool for observing TEP recovery.

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