

CHANGES IN THE SKIN AND ELECTRODE IMPEDANCE SPECTRA DUE TO LONG-TERM SURFACE STIMULATION

Ken Yoshida and Andrei Patriciu

Center for Sensory-Motor Interaction, Aalborg University
Fredrik Bajersvej 7, D3, DK-9220 Aalborg East, Denmark

E-mail: ky@smi.auc.dk, ap@smi.auc.dk

Abstract – *Electrical stimulation using surface electrodes relies on relatively high voltages to attain levels of muscle activation to produce functional limb movements. Prolong periods of FES may result in adverse electrochemical reactions and cause burns to the skin underneath the stimulating electrodes. In an effort to understand the effects of long-term application of stimulation on the skin, we have devised a method to measure the complex impedance of the electrode and tissue to track changes in their impedance. Charge unbalanced stimulation was passed through commercial hydrogel stimulating electrodes placed on shaved porcine skin from the back of the animal. The impedance spectrum of the electrodes and skin were measured before, during and after stimulation. We found that significant changes in the low frequency components of the impedance spectrum coincide with the appearance of burns. The pH of the burns was found to be very acidic ($pH < 3$) under the anode electrode and very basic ($pH > 10$) under the cathode.*

Keywords: Electrical stimulation, skin, burn, gel-type electrodes, impedance spectrum, pH

1. Introduction

Surface electrodes have become the dominant electrodes in clinical use for functional electrical stimulation for the restoration of motor function. Unfortunately, the target tissues for stimulation are the motor fibres in the nerves innervating muscles, which typically lie deep in the limb. Surface stimulation relies, thus, on relatively high voltages to reach and activate these structures. Consequently, a major problem with long-term surface electrode stimulation arises, burns to the skin. The use of high voltage stimulation for prolonged periods of time may result in changes in the electrochemical mechanisms which govern the transfer of charge from electrical to ionic conduction at the electrode interface. The energy in the stimulation can be sufficiently high to dissociate the water in the gel and skin into its constituent ionic components, hydrogen ions under the anode and oxygen or hydroxide ions under the cathode. This, in turn, may result in large changes to the pH and have an adverse effect to the skin and underlying tissues.

A clinically relevant question arises, “Can we find a way to detect changes in the skin or electrode as/before burns occur so that the patient, care provider, or stimulator can be warned and appropriate measures can be taken?” The present study aims to determine whether electrical stimulation initiated burns result in changes to the skin impedance and whether the chemical byproducts of stimulation can be implicated as a factor for the production of these burns.

2. Methods

Complex impedance spectra in this study were measured using a method we have developed. The method uses a two-electrode configuration through which a broad bandwidth noise current waveform is injected. The injected current and voltage drop across the test electrode are sampled (30kHz, 5 Sec) and the Fast Fourier Transforms are computed for these sampled waveforms. The ratio of their Fourier coefficients is calculated to determine the complex impedance spectra of the electrode+skin+tissue between 1 Hz and 10 kHz. The skin+tissue and electrode impedances are differentiated by measuring the electrode impedance by itself by pasting the two test electrodes gel to gel, measuring the electrode impedance spectrum and subtracting this component from the impedance spectrum of the electrode and skin+tissue.

Identical pairs of gel-type stimulating electrodes (Medicotest, type 97-4011A) were applied to freshly excised porcine skin 5 cm apart (10cm center to center). The skin was shaved with an electric shaver prior to removal of the skin from the animal. The impedance spectra of the pre-stimulated electrode and skin were measured using the method described above. A burn producing charge unbalanced stimulus waveform (167us pulse width, 10mA pulse amplitude, 3kHz frequency) or DC was passed through the electrodes and skin for 120 minutes. Using this burn causing stimulation, burns usually develop within 60 minutes and are characterized by blisters resembling 2nd degree burns. Following 60 and 120 minutes of stimulation, stimulation was interrupted, and an intermediate and post stimulation impedance spectra respectively were taken. Following the measurement of the post stimulation impedance spectrum, the stimulating electrodes were peeled off the skin, placed gel to gel and their impedance spectrum

taken. To determine whether large pH changes had occurred, drops of acid (Methyl Orange) and base indicators (Phenolphthalein) were dripped into the burns and onto the electrodes. Changes in the colour of the indicators were noted.

3. Results

Impedance

Large changes in the electrode+skin+tissue impedance are evident after 1 and 2 hours of burn causing stimulation. The gel to gel impedance of fresh electrodes and of electrodes after causing burns shows that there is a significant decrease in the impedance at lower frequencies (fig 1).

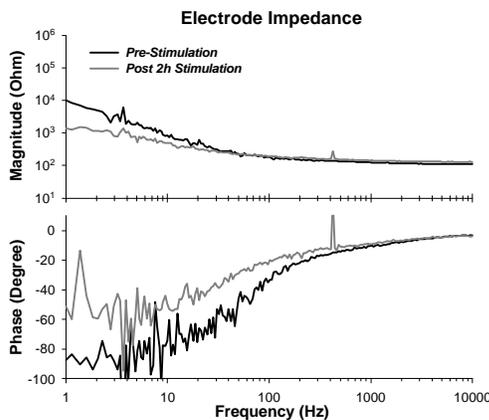


Fig 1: Electrode impedance spectrum before and after 2 hours of burn causing stimulation.

However, these changes are not sufficiently large to account for the large changes seen in the overall electrode+skin+tissue impedance spectrum. After subtraction of the gel to gel electrode impedance spectrum from the electrode+skin+tissue spectrum, we find that there are significant changes in the skin+tissue impedance (fig. 2) at the low frequency portion of the impedance spectrum after burns are induced.

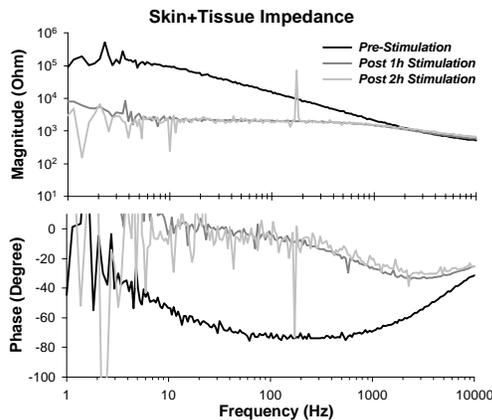


Fig 2: Skin+tissue impedance spectra before, after 1 hour and 2 hour burn causing stimulation. Stimulation results in a decrease in the low frequency portion of the spectrum.

At frequencies above 1kHz, the impedance spectrum shows a purely resistive behavior, indicating that the impedance of the underlying tissue dominates this portion of the spectrum. The impedance of frequencies below 1kHz is dominated by the RC impedance of the skin and barrier layer in the epidermis.

Burns and pH

The changes in the skin+tissue impedance after one hour indicates that burns likely occurred in less than one hour. These burns are characterized by blisters, which form underneath the stimulating electrodes. They typically form under the anode and occasionally under the cathode. Methyl orange and phenolphthalein were used to interrogate the pH of these burns and the surface of the electrode. Methyl orange is an acid indicator, which turns from yellow to red between pH 4 and 3. Phenolphthalein is a base indicator, which turns from colorless to pink between pH 8 and 10. We found that the burns beneath the anode were acidic with a pH less than 3 while the burns beneath the cathode were basic with a pH of at least 10. Similarly, we found that the surface of the anode was also acidic (pH < 3) and the cathode was basic (pH > 10). The pH of the gel of a fresh set of electrodes is slightly acidic but not sufficiently acidic to be indicated by methyl orange.

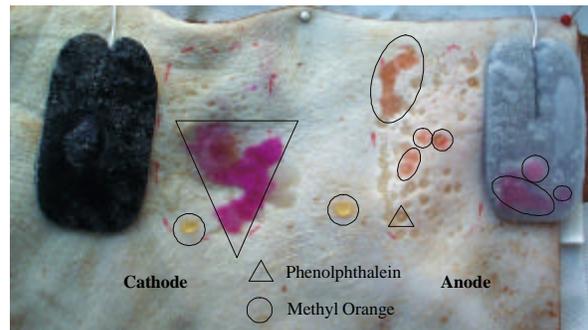


Fig 3: Burns caused by electrical stimulation. Electrodes have been peeled off the stimulation site to expose the gels. Stimulation sites have been marked by dotted lines. Circles indicate burns where methyl orange (acid indicator) has been placed. Triangles indicate locations of burns with phenolphthalein. Note that methyl orange changes color only under the anode and on the gel of the anode, while phenolphthalein changes color only on burns under the cathode and on the cathode.

Indicator drops on the skin itself did not change and is consistent with the near neutral pH of the surface of the skin.

4. Discussion

The change in the frequency dependant component of the skin impedance, which is most pronounced in the low frequency portions of the skin+tissue impedance spectrum is likely due to a breakdown of the barrier layer capacitance in the epidermis of the skin. Breaching this layer changes the impedance to reflect the purely

resistive impedance of the underlying tissue. The change in overall impedance is most pronounced at lower frequencies and is dominated by these changes to the skin impedance. This indicates that it may be possible to detect that a burn has occurred by monitoring the low frequency portion of the impedance spectrum between the two stimulating electrodes. The method used to measure the impedance spectrum for the present study lends itself to direct on-line measurement, as it only requires sampling of the voltage and current waveforms. The only limitation is that it requires that the excitation waveform interrogating the impedance have frequency components with sufficient energy in the range of frequencies of interest. Fortunately, the typical charge balanced biphasic stimulus waveform used in electrical stimulation itself has sufficient energy in the frequency range of interest. This opens the possibility of building stimulators with built-in electrode impedance characterization circuitry with burn detection algorithms.

Electrical mechanisms such as thermal heating and skin dielectric breakdown from the high current and voltages used during stimulation have been the implicated as the most likely explanation for these burns. However, our observations and those of others [1] are that burns typically occur underneath the anode but not the cathode using identical surface electrodes. Given an isolated stimulator, the anode, skin, tissue and cathode are in series with one another there is only one current path. Since the electrode and skin impedances are virtually identical, if electrical thermal heating is the mechanism for these burns, burns should occur on the skin beneath both electrodes. The results of the present study indicate that chemical changes in the electrode

charge transfer mechanisms causing radical pH changes at the electrode skin interface may also play a role. The pH hypothesis can also give a partial explanation of why burns are seen more frequently under the anode electrode. Since the gel in gel-type stimulation electrodes is slightly acidic, the basic ions formed in the cathode must overcome the acidity of the gel before the pH rises to the point where damage to the skin occurs. It still remains to be seen if pH is a mechanism causing burns or whether these changes occur after burns produced by other mechanisms breach the epidermis. If pH plays a role in damaging the skin during stimulation, the safety of surface stimulating electrodes could be improved by incorporating a chemical buffer to the electrode gel to temporarily absorb excess hydrogen or hydroxide ions and maintain the pH for longer periods of time.

Ongoing work focuses on determining whether the pH changes cause burns, the time frame in which pH/impedance changes occur and the measurement of the changes in temperature and pH of the stimulating electrode with more realistic stimulation waveforms.

References

- [1] H. Lambert, E De Baetselier, G.Vanalme and G De Mey. "Skin burn risks using transcutaneous direct current" , *Proceedings of IEEE-EMBC and CMBEC* pp. 647-648, 1995

Acknowledgment: This work was funded in part by grants from the Danish National Research Foundation, Medicotest A/S, and the Danish Academy of Technical Sciences