DETECTING SKIN BURNS INDUCED BY SURFACE ELECTRODES

A. Patriciu[1], K. Yoshida[1], T. P. DeMonte[2], M. L. G. Joy[2]
[1] Center for Sensory-Motor Interaction, Aalborg University, Denmark
[2] Institute of Biomaterials and Biomedical Engineering, University of Toronto, Canada

Abstract - **The origin of electrical burns under gel-type surface electrodes is a controversial topic that is not well understood. To investigate the phenomenon, we have developed an excised porcine skin+gel model. In the present paper, we describe methods to detect these burns in the skin+gel model in an effort to understand the genesis of these burns. Burns were induced by severe electrical stimulation and changes in the impedance spectra and current density measured. We found that the changes in impedance spectrum were characterized by significant drop in the low frequency (<1 kHz) impedance magnitude and the formation of welts in the skin. Low frequency current density imaging (LFCDI) revealed regions of high current density beneath the electrode before burns were induced suggesting the possibility of predicting the locations where welts from burns will form and the importance of current density and local tissue impedance in the formation of these burns.**

***Keywords* - Skin, burn, surface electrodes, impedance measurement, LFCDI, current density**

I. INTRODUCTION

Gel type surface electrodes are the most common electrodes used clinically in applications as diverse as functional electrical stimulation (FES) for the restoration of motor function, to patient ECG monitoring, to defibrillation and surface cardiac pacing. Common to all these applications are occasional reports of rashes or burns on the skin at the points where electrodes were placed. Last year, we reported in [1] a possible chemical mechanism for the production of these burns, and the possibility of using low frequency electrode+skin impedance monitoring to detect when burns are occurring to allow possibility of warning the patient or and/or to preemptively stop stimulation before serious burns occur.

In the present paper, we report on work correlating the change in electrode+skin impedance to changes in current density patterns resulting from burns. We used low frequency current density imaging (LFCDI) to determine the current density distribution across the skin surface under the stimulating electrode before and after the burns were induced

II. METHODOLOGY

Impedance Measurements

Complex impedance spectra in this study were measured using the rapid impedance measurement technique we described previously [1]. The technique yields the electrode impedance spectrum between ~1 Hz and 10 kHz with short 1-10 second measurements. Shortly, bandwidth limited noise current is passed through one surface electrode, through the skin, tissue, and back through the counter electrode. The current through the test electrode and the voltage drop across the electrode+skin+tissue are simultaneously measured. Fast Fourier Transforms are taken of the appropriately sampled (30kHz, 5sec) and windowed voltage and current waveforms, and the empirical transfer function estimated. This estimate directly yields the impedance spectrum of the electrode+skin+tissue. The method is repeated with the two electrodes attached gel to gel to estimate the electrode impedance. The estimated electrode impedance is then subtracted from the electrode+skin+tissue impedance to derive the skin+tissue impedance.

LFCDI Measurements

LFCDI is a technique [2], which allows the direct visualization of volumetric current flow within an object, or within the body. The technique makes use of the phase information in magnetic resonance imaging (MRI). The object is imaged while it is being actively electrically stimulated with imaging current pulses. This imaging process is repeated in two orthogonal directions. This requires the object being measured be small enough to fit within the bore of the MRI magnet. To investigate the genesis of burns, we have developed an excised porcine skin+gel model and use the LFCDI technique

Skin+Tissue Model

The experimental skin+tissue model consisted of a Plexiglas box (15x14.5x7 cm) containing an homogeneous gelatin slab with a piece of porcine skin covering the top surface (Fig.1). Similar to [1] and [2] the gel was prepared using 1.5 l distilled water, 200 g gelatin (MERCK Eurolab) and 3.37 g NaCl to obtain a gel with a conductivity of 0.74 S/m. 13.6 ml of formaldehyde was added as a preservative. The resulting homogenous gel mimics the electrical conductivity of the subcutaneous soft tissue. A freshly excised patch of porcine skin (14x15 cm) was placed on the top surface of the gel slab, with care taken not to trap air

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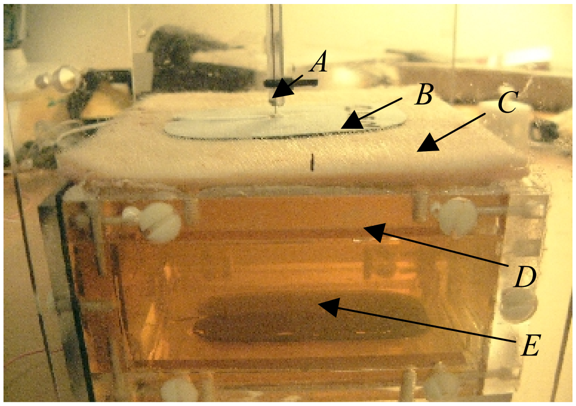

Fig 1. Experimental Skin+Tissue model: (A)attachment, (B) test electrode, (C) porcine skin, (D)– gelatin, (E) counter electrode.

bubbles. The skin patch was visually clear of scars and blemishes. The subcutaneous fat layer was relatively constant in thickness. Prior to excising the skin was electrically shaved. Identical pairs of gel-type stimulating electrodes (Medicotest, Type 97-2631A) were applied to the top skin patch and bottom side of the gel slab. Both electrodes were connected to an electrical stimulator that delivers the imaging current pulses. A special attachment was used to connect the upper electrode in order to minimize LFCDI artifacts.

General Method

A photograph was taken of the surface of the skin to record its features before the procedure. Surface electrodes were attached to the skin and the electrode+skin+gel impedance was measured. Following measurement of the impedance spectrum, the current density (CD) distribution perpendicular to the skin surface was imaged. We used 10 mA bipolar square current pulses of 22 ms duration, synchronized with a spin echo MRI sequence. The MRI parameters were TR=2000 ms, TE=30 ms and voxel dimension of 1.02 x 1.02 x 2 mm. These three measurements comprised the pre-burn dataset.

After the pre-burn data was collected, burn-inducing stimulation was carried out using a 200 Hz, 70 % DC, 40 mA monophasic square waveform applied to the electrodes for 60 min. The electrode placed on the skin was made in half of the trials and the cathode in the remaining trials.

Impedance spectrum and current density image were taken, the electrode peeled off the skin, and a photograph taken to complete the post-burn dataset. Finally, the used electrodes were placed gel to gel and their impedance spectrum determined to characterize the electrode impedance. The current density and impedance spectra were post-processed using MATLAB to arrive at the current density distributions and skin+gel impedance spectra.

III. RESULTS

It is well known that the outermost layer of the skin, the stratum corneum, exhibits a parallel RC behavior [5]. At low frequencies this yields high impedance. Typical magnitude and phase components of the skin+gel impedance before the burn inducing stimulation are shown in Fig 2 (thin line).

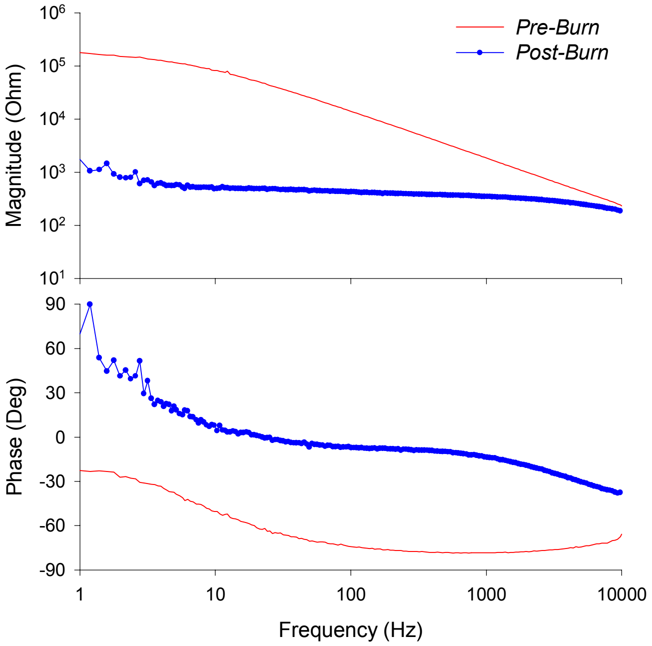

Fig. 2. Typical impedance spectrum represented as magnitude and phase plots showing skin+gel impedance before (thin line) and after (thick line) 1 hour of burn inducing stimulation.

Burns induced by monophasic electrical stimulation breaks down the skin capacitance and results in a skin impedance which is more resistive in behavior. This suggests that the capacitive behavior of the stratum corneum is lost and that of underlying tissue dominates the post burn impedance spectrum. The change in impedance is most marked in the impedance spectra of frequencies < 1 kHz.

Fig. 3A shows a typical uniform, blemish free surface, of the skin before burns were induced. Fig. 3B is the same skin after stimulation, showing welts characteristic of electrically induced burns. They are apparently randomly distributed and cannot be predicted by the photo record (Fig. 3A). More detailed information about the current flow across the skin could be obtained analyzing the CD images. Values of the current density computed before stimulation on the intact skin surface (Fig. 3C) are compared to the post burn distribution. (Fig. 3D) Despite the improved wire connection to the top surface electrode, artifacts attributed to high local current density values and tilting of the lead wire are observed in the middle of the electrode.

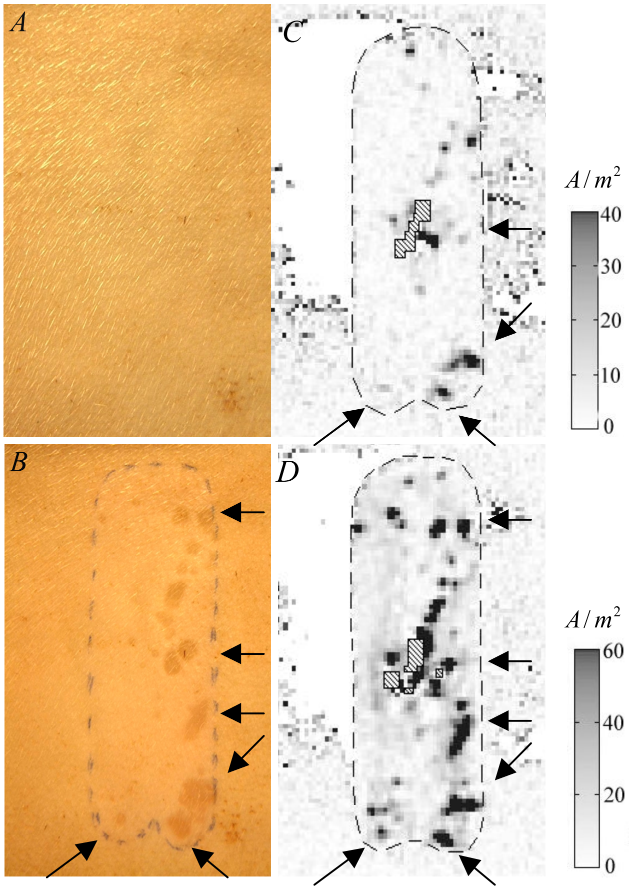

Fig 3.Pictures of the skin and the current density distribution of the same area before (A &C) and after (B &D) burns. The dotted line marks the electrode placement during the experiment. Hatched voxels represent regions masked out due to artifacts. Arrows point to points of high current density and welts formed by burn causing stimulation.

IV. DISCUSSION

Changes in the skin+tissue impedance could be evidenced using the impedance spectrum measurements. There is a significant drop in magnitude at lower frequencies, and changes encountered in the phase diagram, suggesting the breakdown of the barrier layer capacitance in the skin epidermis. Line monitoring of the skin impedance can predict the onset of the burns and may one day be used as a method to prevent harmful electrical stimulation. Visual examination of the skin surface before the onset of the burn does not suggest any possible current paths. The blisters and morphological changes of the skin occur randomly and cannot be predicted. These two observations predict high current densities at blisters or welts.

LFCDI confirms this prediction. Comparison of the CD images with the pictures taken from the skin after the onset of the burns shows a very clear correlation between the position of the burns and the high current regions. This explains also the impedance decrease that was observed. Moreover, analysis of the current density distribution before and after the burn inducing stimulation shows something unanticipated. Remarkably, the measurement is sensitive enough to show regions of high current densities i.e. regions with lower electrode-skin impedance in the pre-burn skin. These areas correlate with areas where burn welts were produced and thus predict regions where burns are likely to occur. In these regions of high current density, locally aggressive changes in pH as we reported in [1] could occur and lead to the onset of burns. We are currently investigating these regions to determine the genesis of electrically induced burns to improve surface electrode design and safety.

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