

# Current Densities Produced by Surface Electrodes: Comparison of MRI measurements and Finite Element Modeling

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## Introduction

Surface electrodes are flexible pads placed on the skin that are used to inject electrical current into tissue. This electrical current is used to activate excitable cells for such medical purposes as pain relief and neuromuscular stimulation. To design more effective surface electrodes, a more thorough understanding of the current pathways in tissue produced by the electrodes is needed.

This abstract describes two independent methods that were used to obtain current density maps inside a tissue-mimicking gel. The first method employs a finite element method (FEM) to simulate the current densities within the volume. The second method employs magnetic resonance imaging (MRI) to measure the magnetic fields associated with the injected current. The current densities in the volume can be computed from these magnetic field maps using a technique called current density imaging (CDI) [1].

## Methods

Different pairs of gel type surface simulating electrodes (Medicostest A/S) were applied on a tissue-mimicking homogeneous animal hide gelatine slab, placed in a 243x165x48 mm plastic container (Fig 1(a)). Similar to [2] and [3], the gel was prepared using 1900 ml of distilled water, 252 g animal hide gel and 10 ml of formaldehyde. 4.27 g of NaCl were added to obtain a conductivity of 0.55 S/mm. The result was a homogenous gel, mimicking soft tissue in terms of its MRI properties (T<sub>1</sub> & T<sub>2</sub>) and electrical conductivity.

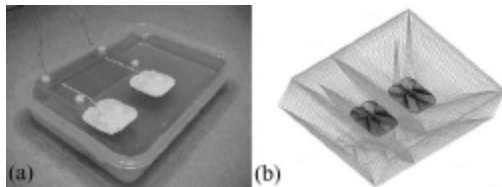
**FEM Simulation:** Based on the electrical and geometrical properties of the different constitutive materials, the FE method has been used to simulate the CDI measurements. The mesh was generated using OPERA-3d [4] commercially available software package and Tosca as a finite element solver (Vector Fields). The solution of the current conduction problem was obtained by solving Laplace's equation:

$$\nabla \cdot (\sigma \nabla V) = 0 \quad \text{Eq. 1}$$

where  $\sigma$  is the conductivity and

$$\mathbf{J} = -\sigma \nabla V \quad \text{Eq. 2}$$

As Neumann's boundary condition, a current of 100 mA was assumed through the surface of the electrode and no current in or outflow through the sidewalls of the slab. The model was constructed using linear hexahedral elements. Fig 1(b) shows the generated mesh for the electrode type 97-2331A.



**Fig 1: Experimental setup showing electrodes placed on the gel (a) and the corresponding FE model (b)**

Current density values were extracted (computed) in nodes corresponding to the MRI voxel positions and compared to the CDI measurement.

**CDI Measurement:** The magnetic fields produced by an externally injected current mix with the magnetic fields produced by MRI gradients and the results are apparent in the phase image. Only the component of magnetic field that is parallel to the static B<sub>0</sub> field can be measured. According to Eq. 3, two components of magnetic field,  $\mathbf{H}$ , are required to compute a single component of current density,  $\mathbf{J}$ . To achieve this measurement, two orthogonal orientations of the sample are required within the MRI system.

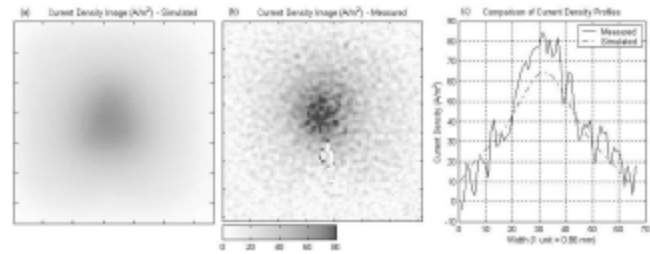
$$\mathbf{J} = \nabla \times \mathbf{H} \quad \text{Eq. 3}$$

For this experiment, square current pulses of duration 24ms and amplitude 100mA were synchronized with a spin echo MRI sequence. The MRI parameters were TR=600ms, TE=30ms and voxel

dimensions: 0.86 x 0.86 x 2mm. The slice plane was parallel to the surface of the electrode and centered about 5mm below the surface of the gel.

## Results

A comparison of the current density images obtained from the FEM simulation and CDI measurement are given in Figs 2(a) and 2(b), respectively. These spacial images display the magnitude of the current density component orthogonal to the electrode surface. As a further comparison, profiles were taken across the width of the images near the middle of the electrodes as shown in Fig 2(c).



**Fig 2: Current densities 5 mm below gel surface. (a) Simulated. (b) Measured. (c) Comparison of current density profiles.**

## Discussion

The results of the two techniques are similar. The profiles of Fig 2(c) are within 15%. The CDI measurement technique can potentially be used for in-vivo measurement of tissue, whereas the FEM simulation becomes increasingly more complicated and less reliable as more nuances of heterogeneous tissue are added to the model. It is difficult to define the exact regions of differing conductivities, required by an FEM model, due to complexity of the tissue.

The CDI measurement technique has shortcomings that fall under two categories: noise and artifacts. Noise is apparent in Fig 2(b)&(c). To quantify CDI noise, a standard deviation of 5.1 A/m<sup>2</sup> was measured in an experiment where no current was applied. Artifacts include several of the known MRI artifacts such as susceptibility and RF shielding as well as new artifacts associated with the CDI technique. These include image registration and high phase gradients. Image registration must be performed on a sub-pixel level in regions of high current density gradients to obtain correct results. High phase gradients refers to the amount of phase shift over a single pixel in the phase image. A phase shift of more than  $\pi$  across a pixel cannot be resolved properly by basic unwrapping techniques. A phase shift of  $2\pi$  across a pixel causes MRI signal cancellation and severely degrades the MRI signal-to-noise ratio (SNR).

The good match between the simulation and measurement is encouraging. The experiment described in this abstract demonstrates the potential for using CDI to measure the effectiveness of surface electrode designs. The technique is presently limited by noise and artifacts. The artifacts discussed above, become more severe as images are taken closer (<5mm) to the surface electrode.

## References

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