INVESTIGATION OF CURRENT DENSITIES PRODUCED BY SURFACE ELECTRODES USING FINITE ELEMENT MODELING AND CURRENT DENSITY IMAGING

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

***Abstract* – Designers of gel-type surface electrodes, used in medical applications such as pain relief and neuromuscular stimulation, require a more thorough understanding of current pathways in tissue in order to design more effective electrical stimulation systems. To investigate these pathways, a finite element model (FEM) was used to compute current density distributions produced by an electrode placed on the surface of a homogeneous, tissue-mimicking gel slab. The gel slab phantom was constructed and the current densities were measured using a recently developed technique called current density imaging (CDI). CDI uses the phase data produced by magnetic resonance imaging (MRI) as a measure of the magnetic fields produced by the externally applied current. The results of the FEM simulation and CDI measurements compare well. CDI has several potential advantages over conventional FEM techniques including: no requirement for knowledge of local tissue conductivities, low and constant computational overhead regardless of tissue complexity, and the potential to perform in-vivo measurements.**

***Keywords* – Surface electrode, modeling, finite element method, current density imaging**

I. 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 medical purposes such as pain relief and neuromuscular stimulation. Researchers and designers of surface electrodes require a more thorough understanding of the current pathways in tissue to design more effective surface electrodes.

As a first step towards investigating current pathways in tissue, two independent techniques were used to obtain current density maps inside a tissue-mimicking gel. The first technique employs a finite element method (FEM) to simulate the current densities within the volume. The second technique, called current density imaging (CDI), measures the magnetic fields generated by the current flowing in the tissue using magnetic resonance imaging (MRI) and computes the current densities from these fields [1].

Presently, FEM simulations are the most common approach to this type of problem. For an FEM simulation to produce accurate results, local tissue conductivities must be known or estimated. Inaccurate knowledge of these conductivities leads to inaccurate results in field computations. The inherent complexity of tissue makes FEMs computationally demanding. CDI is relatively new technique that offers some potential advantages over FEM. First, CDI is a measurement technique, as opposed to a simulation, that can potentially be used in-vivo. Second, CDI is only concerned with magnetic fields and current densities and does not require knowledge of local conductivity. Finally, the computational overhead of CDI, which is far less than that of a simple FEM, remains constant regardless of the complexity of tissue. An obvious drawback is that an MR imager is required for CDI.

II. METHODOLOGY

Different pairs of gel-type surface stimulating electrodes (Medicotest A/S) were applied on the top and bottom of a tissue-mimicking homogeneous gelatin slab, placed in a 15 x 14 x 7 cm phantom (Fig. 1). Similar to [2] and [3], the gel was prepared using 1.5 l of distilled water, 200 g gelatin (MERCK Eurolab) and 7.9 ml of formaldehyde. 3.37 g of NaCl was added to obtain a conductivity of 0.74 S/m. The resulting gel was homogenous with conductivity close to that of typical soft tissue. Both electrodes were connected to an electrical stimulator that delivers the imaging current pulses. A special attachment (Fig. 1) was used to connect the upper electrode in order to minimize LFCDI artifacts.

FEM Simulation

The geometry and electrical properties of the electrodes, gel and phantom were used to simulate the CDI measurements. The mesh was generated using OPERA-3D [4], a commercially available software package, and TOSCA

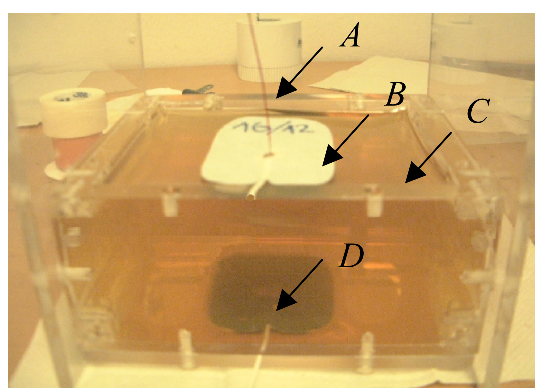

Fig 1. Experimental setup. The arrows mark the: (A) attachment , (B) electrode, (C) gelatin, and (D) counter electrode

This research was supported by the Danish Academy of Technical Sciences.

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25OCT2001	N/A	-

Title and Subtitle Investigation of Current Densities Produced by Surface Electrodes Using Finite Element Modeling and Current Density Imaging	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Center for Sensory-Motor Interaction, Aalborg University, Aalborg, Denmark	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Papers from the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom., The original document contains color images.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 4	

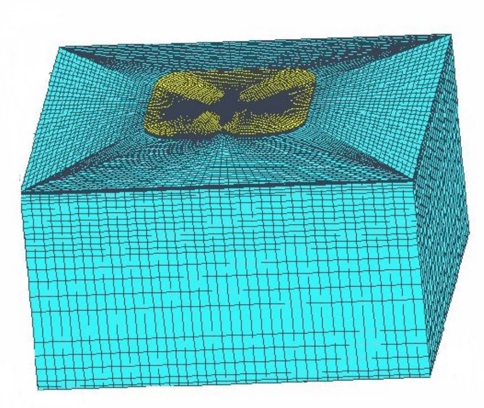

Fig.2. FEM model

as a finite element solver (Vector Fields). The solution of the current conduction problem was obtained solving Laplace's equation:

$$\nabla \cdot (\sigma \nabla V) = 0 \qquad (1)$$

where σ is the conductivity. Current density was computed using:

$$\mathbf{J} = -\sigma \nabla V \qquad (2)$$

The boundary conditions applied to the model were no current in or outflow through the sidewalls of the gelatin box and a 50 mA current was assumed through the surface of the electrodes. This value matches the current applied during the experiment. The model was constructed using hexahedral elements. The generated mesh is presented in Fig. 2. Current density (CD) values were computed at nodes that correspond to the voxel locations in the MRI data used in the CDI technique.

CDI Measurement

Electrical currents externally applied to a sample, during an MRI acquisition, will generate magnetic field components parallel to the main field, B_0, of the MRI system. These components will be encoded in the phase image(s) of the

$$\mathbf{J} = \nabla \times \mathbf{H} \qquad (3)$$

MRI data. Cartesian expansion of Equation (3) indicates that two orthogonal components of the magnetic field, **H**, are required to compute one component of current density, **J**. In practice, two orthogonal orientations of the sample are required in the MRI system to compute one component of the current density.

In this experiment, square current pulses of duration 24 ms and amplitude of 50 mA were synchronized with a spin echo

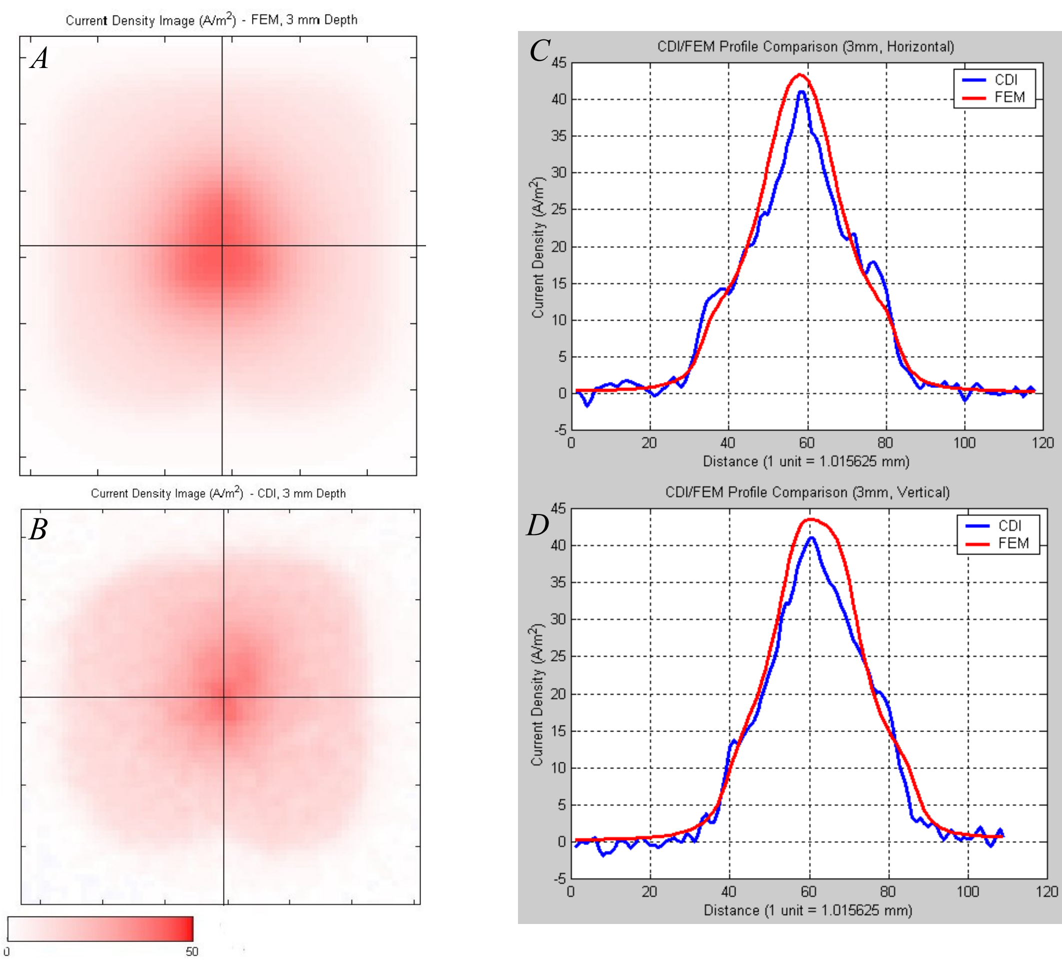

Fig 3 Current density images 3 mm below the electrode surface.
-(A) simulation, (B) CDI measurement, (C), (D) line plots across the horizontal and vertical section

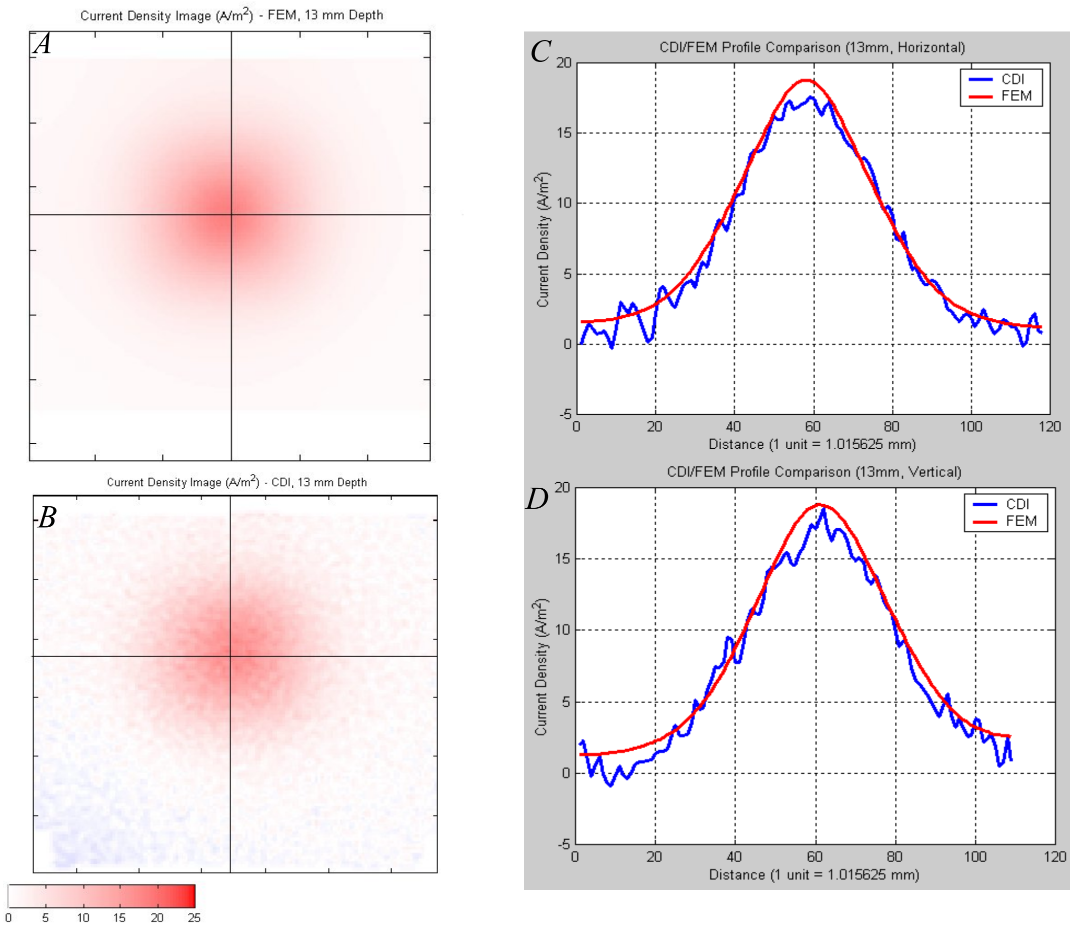

Fig 4. Current density images 13 mm below the electrode surface.
-(A) simulation, (B) CDI measurement, (C),(D) line plots across the horizontal and vertical section

MRI sequence and applied to Medicotest Type 97-2331A electrodes. The MRI parameters were TR=1500 ms, TE=30 ms and voxel dimensions of 1.02 x 1.02 x 2 mm. The slice planes were parallel to the surface of the electrode.

III RESULTS

Images of the current density component, orthogonal to the surface of the electrode are represented for two different slice planes, at 3 and 13 mm under the surface of the electrode. Fig. 3A and Fig. 3B show the images generated by the FEM simulation and the CDI measurement at a depth of 3 mm. As a further comparison between the two techniques, horizontal and vertical profiles were taken across these images and plotted together in Fig. 3C and Fig. 3D respectively. Similar images are shown for the plane at 13 mm below the electrode surface in Fig. 4.

IV DISCUSSION

The results of the two techniques are very similar. The peaks of the profiles are within 5 % of each other with the FEM generally showing higher values. Integration of the surfaces yields results that are within 10 % of each other with the FEM generally showing higher values.

The CDI measurement technique has shortcomings that fall under two categories: noise and artifacts. The noise is apparent in Fig. 3B, Fig. 4B and the horizontal and vertical profiles. To quantify CDI noise, an experiment was performed with zero current. The measurements then showed a standard deviation of about 1 A/m^2. 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 new artifacts 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 refer to the amount of phase shift over a single pixel in the phase image. A phase shift of more than π across a pixel cannot be resolved properly by basic unwrapping techniques. A phase shift of 2π 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 of using CDI to measure the effectiveness of surface electrode designs. Noise and artifacts presently limit the technique. The artifacts discussed above, become more severe as images are taken closer (< 3 mm) to the surface electrode.

ACKNOWLEDGMENT

The authors would like to thank Dr. H Stødkilde-Jørgensen and F. T. Jensen from MR Research Centre Aarhus University Hospital, Denmark for their help for running the MRI experiment, J. Stavnshøj for technical support, Medicotest A/S for the provided stimulation electrodes and Sunnybrook and Women's College Health Sciences Centre, Canada, for providing the facilities for the initial experiments.

REFERENCES

[1] G.C. Scott, M.L.G. Joy, R.L. Armstrong, and R.M. Henkelman "Sensitivity of Magnetic-Resonance Current-Density Imaging" in J. Mag. Res. Vol. 97, pp. 235-254 1992

[2] J.C.Blechinger, E.L.Madsen, and G.R.Frank "Tissue-mimicking gelatin-agar gels for use in magnetic resonance imaging phantoms" in Med.Phys.15 (4) Jul/Aug 1988

[3] L.A.Geddes,and L.E.Baker "The specific resistence of biological material- a compendium of data for the biomedical engineer and physiologist" in Med & Biol. Eng. Vol. 5, pp. 271-293 1967

[4] Vector Fields Ltd. Opera 3d User Manual 24 Bankside Kidlington Oxford England