

## Mini-Symposia Title:

Verification and Validation of Computational Models in  
Electrotherapeutics

### Mini-Symposia Organizer Name & Affiliation:

Marc Horner, Ansys, Inc. & Punit Prakash, Kansas State  
University

### Mini-Symposia Speaker Name & Affiliation 1:

Punit Prakash, Dept of Electrical and Computer Engineering,  
Kansas State University

### Mini-Symposia Speaker Name & Affiliation 2:

Ravi L. Hadimani, Department of Mechanical and Nuclear  
Engineering, Virginia Commonwealth University

### Mini-Symposia Speaker Name & Affiliation 3:

Laleh Golestani Rad, Department of Biomedical Engineering,  
Northwestern University

### Mini-Symposia Speaker Name & Affiliation 4:

James Brown, Biotronik

### Mini-Symposia Speaker Name & Affiliation 5:

Tal Marciano, Novocure

### Mini-Symposia Speaker Name & Affiliation 6:

## Theme:

- 01. Biomedical Signal Processing
- 02. Biomedical Imaging and Image Processing
- 03. Micro/Nano-bioengineering: Cellular/Tissue Engineering &
- 04. Computational Systems & Synthetic Biology: Multiscale modeling
- 05. Cardiovascular and Respiratory Systems Engineering
- 06. Neural and Rehabilitation Engineering
- 07. Biomedical Sensors and Wearable Systems
- 08. Biorobotics and Biomechanics
- 09. Therapeutic & Diagnostic Systems and Technologies
- 10. Biomedical & Health Informatics
- 11. Biomedical Engineering Education and Society
- 12. Translational Engineering for Healthcare Innovation and Commercialization

### Mini-Symposia Synopsis— Max 2000 Characters

Electromagnetic therapies rely on the targeted energy deposition as a medical treatment for a variety of pathological conditions in humans. Treatments include tumor-treating fields, electroconvulsive therapy, electrical neuro-stimulation, deep-brain stimulation, magnetic stimulation, and thermal therapies. In each of these applications, there is a desire to understand the ability of the therapeutic system to target the electrical energy to a specific site(s) within the human body. The safety of each treatment modality must also be considered since the interaction between applied electromagnetic energy and human tissue may cause tissue heating and potentially irreversible tissue damage. While benchtop experiments in phantoms and in vivo animal testing can provide some insights into the potential safety and efficacy of a therapeutic technology, these testing environments may differ considerably from the tissue anatomic and physiologic state in humans. For example, ex vivo tissue models typically do not account for the effects of blood perfusion, and animal models may not provide a suitable representation of the disease in humans. Meanwhile, testing of therapeutic systems in humans is often not possible without exposing test subjects to potential harm.

Computational modeling and simulation tools offer strong potential to serve as a platform for evaluating the safety of electromagnetic therapeutic systems with no patient harm, but model credibility remains a challenge. The processes of verification, validation, and uncertainty quantification (VUQ) provide a methodology for establishing that a model is credible for decision-making. This mini-symposium will include presentations that review current VUQ best practices, as well as academic, industrial, and clinical studies that include verification and/or validation approaches to establish model credibility for a variety of electromagnetic therapeutic systems.

# Validation of computational models of microwave thermal ablation with MRI thermometry

Pegah Faridi, Paul Keselman, and Punit Prakash, Dept of Electrical and Computer Engineering, Kansas State University, USA

**Abstract—** Computational models of microwave thermal ablation are widely used for guiding the design and optimization of new applicator designs, for comparative assessment of energy delivery strategies, to characterize applicator and system performance as part of regulatory submissions, and are under development for personalized planning of ablation treatments. Validation of computational models is often performed by comparing the size and shape of ablation zones predicted by models with experimental observations. Magnetic resonance imaging (MRI) thermometry offers a means for non-invasive volumetric imaging of temperature profiles, and thus has potential to serve as a means for experimental validation of transient temperature profiles predicted by computational models. This presentation will discuss the integration of a custom 2.45 GHz, water-cooled, microwave ablation system with 3 T MRI. MRI thermometry with the proton resonance frequency shift (PRFS) technique was used to characterize transient temperature profiles in fresh *ex vivo* tissue following 5 – 10 min ablation. The uncertainty in MRI thermometry was 0.3 – 0.7 °C. The Dice Similarity Coefficient between thermal damage profiles computed from MRI thermometry and simulations ranged between 0.75-0.8. Large artifacts in MRI thermometry were observed in regions at temperatures > ~90 °C, attributed to water vaporization. In summary, MRI thermometry offers strong potential to characterize volumetric temperature profiles predicted by computational models of microwave ablation.

## I. INTRODUCTION

Computational models are widely used during the design and characterization of microwave ablation applicators, and have been proposed for use with personalized treatment planning platforms. The objectives of the present work were to: (1) develop an experimental microwave ablation platform integrated with magnetic resonance imaging (MRI) thermometry at 3T, and (2) employ the platform for comparative assessment of thermal damage profiles predicted by state-of-the-art computational models vs. MRT measurements in *ex vivo* tissue.

## II. METHODS

We performed microwave ablation in *ex vivo* tissue (bovine liver and porcine muscle) under MRI thermometry guidance using a custom, 2.45 GHz water-cooled applicator. MRI thermometry data were acquired on a 3T Siemens Skyra scanner in one coronal and two axial planes using a series of FLASH images (TR/TE = 50/12.3 ms, FOV = 128 x 128

mm<sup>2</sup>, matrix = 128 x 128, flip angle = 15°, slice thickness = 1.5 mm and acquisition time = 6.4 s). Data were acquired for 2 min prior to heating, during 5-10 min microwave exposures, and for 3 min following heating. Fiber-optic temperature sensors were used to validate the accuracy of MRI thermometry data. A total of 15 ablation experiments were conducted using 30–50 W applied power. Microwave ablation computational models were implemented using the finite element method, and incorporated temperature-dependent changes in tissue physical properties. Model-predicted ablation zone extents were compared against MRI thermometry-derived Arrhenius thermal damage maps and visually observed ablation zones using the Dice similarity coefficient (DSC).

## III. RESULTS

Prior to heating, the observed standard deviation of MRI thermometry data was in the range of 0.3- 0.7 °C, similar to previously reported uncertainty in other studies. Mean squared error between MRI thermometry and two fiber-optic sensors during heating was in the range of 1 – 2.8 °C and 0.5 – 1.4 °C, respectively. DSC between model-predicted ablation zones and MRI thermoemtry derived Arrhenius thermal damage maps were  $0.8 \pm 0.0$  (30 W, 10 min,  $n=4$ ),  $0.8 \pm 0.08$  (30 W, 5 min,  $n=8$ ) and  $0.75 \pm 0.06$  (50 W, 5 min,  $n=3$ ). High power microwave exposure,  $P > 40$  W ( $n=4$ ) was associated with extensive water vaporization in proximity to the applicator, which corrupted MRT data in these regions.

## IV. DISCUSSION & CONCLUSION

We have developed a system for 2.45 GHz MWA integrated with MRT at 3T and applied the system towards experimental validation of MWA computational models.

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The authors are with: Department of Electrical and Computer Engineering, Kansas State University (P.F., P.P.) and the Hoglund Brain Imaging Center, University of Kansas Medical Center (P. K.)

# Development and Characterization of an Accurate Human Brain Phantom

Hamzah A. Magsood, *Student Member, IEEE* and Ravi L. Hadimani, *Senior Member IEEE*

**Abstract**— an anatomically accurate brain phantom was fabricated for measurement of stimulation strengths during transcranial magnetic stimulation (TMS). Measured induced voltages on the phantom during TMS are compared to e-field calculations from FEM simulation. The stimulation strength measured in induced voltage vs. TMS coil current density show similar trend with induced electric field vs. TMS coil current density. This indicates that the brain phantom can be used to study stimulation strengths in neuromodulation techniques like TMS.

## I. INTRODUCTION

Transcranial Magnetic Stimulation (TMS) is a non-invasive technique for diagnostics and treatments of various neurological diseases [1, 2]. However, the lack of anatomically realistic brain phantoms has made the experimental verification of stimulation intensity in the brain tissues an impediment to the development of new treatment protocols. We have developed a 3-D anatomically accurate brain phantom that can mimic the averaged electrical conductivity of the brain [3].

The anatomically accurate brain phantom will enable the professionals in the field of the neuromodulation to test and perform brain stimulations on the phantom that are accurate and match the clinical setting of the of TMS treatments. The electrical conductivity of the brain phantom is 0.25 Sm<sup>-1</sup>. The phantom is examined under different TMS parameters and compared with FEM modelling of induced electric and magnetic fields in the brain.

## II. METHODS

We have developed a conductive polymer nanocomposite material using PDMS and MWCNT that mimic conductivities of different regions of a human brain. An anatomically accurate brain phantom with an adjustable electrical conductivity matching the averaged conductivity of white matter and grey matter of the human brain. The process of producing the phantom starts with segmenting the MRI images of the brain and then creating shells from the segmented and reconstructed model ready for 3-D printing and serving as a mold for the conductive polymer. The induced voltage is the difference between the voltage induced on ‘phantom+probe’ and the probe. This indicates there is a noticeable induced electric field in the phantom due to the applied magnetic field of TMS coils. Finite Element simulations were also carried out in SIM4Life software to

determine the induced electric fields in the brain and compared against the measurements.

## III. DISCUSSION & CONCLUSION

Fig.1 shows induced voltage in the phantom vs. coil current and induced voltage in the phantom vs. distance from the phantom. These results show similar behavior our FEM simulations. We have demonstrated that stimulation strengths in TMS can be experimental verified by our brain phantom.

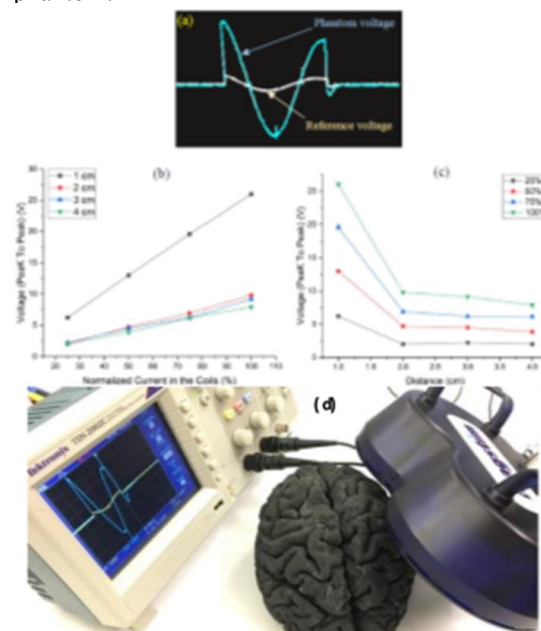


Figure 1. (a-c) Voltage and e-field readings (experimental and simulation) with varied distances (1-4cm) and intensities (25-100%) (d) Measurement set-up.

## ACKNOWLEDGMENT

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H. A. Magsood, and Ravi. L. Hadimani are with the Mechanical and Nuclear Engineering Department, Virginia Commonwealth University, Richmond, VA 23220 USA (corresponding authors phone 541-790-1569 and 804-828-3679; e-mail: magsoodha@vcu.edu and rhadimani@vcu.edu)

# RF heating of deep brain stimulation implants during MRI: in-silico simulations that changed the surgical practice

Laleh Golestanirad, Northwestern University

**Abstract—** Patients with medical implants such as those with deep brain stimulation (DBS) devices can highly benefit from magnetic resonance imaging (MRI), however access to MRI is restricted in these patients due to safety risks. The main hazard is the RF heating of tissue due to the “antenna effect”, where the electric field of MRI scanner couples with implanted leads and amplifies energy deposition in the tissue surrounding the tip. Here we show that validated MRI models can reliably predict patient-specific RF heating of DBS implants across a range of MRI transmit frequencies (64MHz-127MHz).

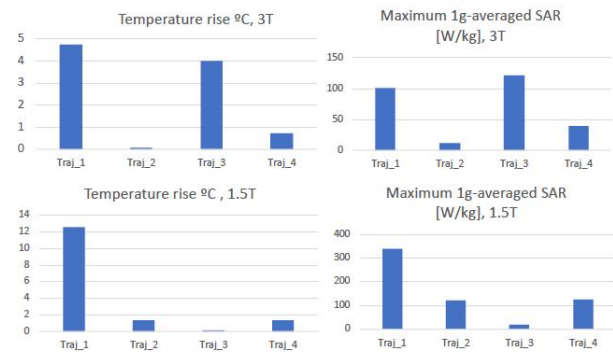
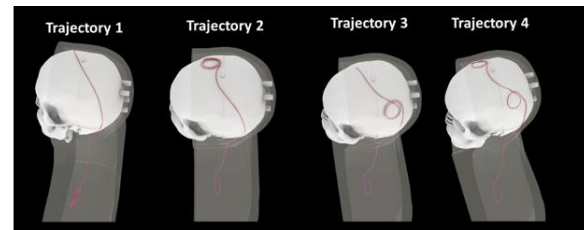
## I. INTRODUCTION

Patients with deep brain stimulation (DBS) implants can significantly benefit from magnetic resonance imaging (MRI), both for electrode localization and for ruling out complications. Unfortunately, however, MRI is not freely accessible to these patients due to safety hazards associated with RF heating of the implant. The major risk is the “antenna effect”, where the electric field of MRI transmit coil couples with DBS long leads and extensions and amplifies the specific absorption rate (SAR) of radiofrequency energy in the tissue around electrode contacts. Recently, we showed that there is a substantial patient-to-patient variation in the local SAR at tips of isolated DBS leads (lead-only system) depending on lead’s trajectory [1]. Specifically, trajectories where the extracranial portion of the lead was looped on the skull showed a highly reduced SAR during MRI at both 1.5T and 3T. Here we demonstrate that presence of extracranial loops reduces RF heating of fully implanted DBS systems (lead+extension+IPG) at both 1.5T and 3T scanners, and that the optimum location of the loop can be predicted by numerical simulations. Moreover, both simulations and measurements show that DBS RF heating does not increase by increasing MRI field strength (or RF frequency) which has been a common misconception in the past.

## II. METHODS

We designed and constructed an anthropomorphic head and torso phantom, implanted with a commercial Medtronic DBS system (Medtronic Inc, Minneapolis, MN) consisting of a lead (3387, 40 cm), an extension (3708660, 60 cm), and an IPG (Activa PC-37601). Two fluoroptic temperature probes (ONSENSA, BC, Canada) were secured to contact-0 (most distal) and contact-2 of the lead to measure temperature rise during MRI at 1.5T and 3T in Siemens Area 1.5 T and Siemens Prisma 3T scanners (Siemens Healthineers, Erlangen, Germany). Four different lead-extension trajectories were investigated for RF heating as illustrated in Figure 1.

Simulations were performed using ANSYS Electronic Desktop (ANSYS, Inc, Canonsburg, PA).



## III. RESULTS

Simulations perfectly predicted the measurement results. Presence of loops in the extracranial portion of the DBS lead reduced RF heating during MRI at both 1.5T and, although the optimum location of the loop for maximum effect was different for 1.5T and 3T. Looping the lead over the temporal bone (Trajectory 3) maximally reduced RF heating at 1.5T MRI. This configuration however, was not optimal at 3T, where looping the lead on top the head at the surgical burr hole maximally reduced RF heating.

## IV. CONCLUSION

Numerical simulations provide an exquisite tool that allows systematic evaluation of dependency of RF heating on patient, implant and MRI coil characteristics and thus, can provide invaluable information for patient-specific risk assessment.

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L. Golestanirad is with the Departments of Biomedical Engineering and Radiology, Northwestern University, Chicago 60611, IL, USA, e-mail: [Laleh.rad1@northwestern.edu](mailto:Laleh.rad1@northwestern.edu) ).

# MRI Safety of Active Implantable Medical Devices: Numerical Study of the Effect of Lead Insulation Thickness on the RF-induced Tissue Heating at the Lead Electrode

James E. Brown, *Member, IEEE*; Harish Kamineni, *Student Member, IEEE*; Paul J. Stadnik, *Sr. Member, IEEE*; Larry J. Stotts, *Sr. Member, IEEE*; Jeffrey A. Von Arx, *Member, IEEE*; and Krishna K. N. Kurpad, *Member, IEEE*

**Abstract**— Among the potential hazards of MRI for patients with an active implantable medical device (AIMD) is RF-induced tissue heating at the lead electrode [1]. The *in vivo* RF-induced tissue heating is typically estimated through the use of computational human models [2]. For leaded AIMDs, the accuracy of the predicted RF-induced tissue heating is dependent on the tissue simulating medium (TSM) used during transfer function model (TFM) development [3-4]. This work explores the impact of the TSM as a function of lead insulation thickness, through the use of a realistic lead geometry for cardiac applications in three different TSMs. The simulation results are verified through comparison with *in vitro* measurement of each lead with the nominal insulation thickness.

## I. INTRODUCTION

The Tier 3 procedure [1] for testing electrically long active implantable medical device (AIMDs) for MRI RF safety involves the development of transfer function models (TFM) for AIMDs [5-6]. The electrical properties of the tissue simulating medium (TSM) in which the TFMs are developed have a huge impact on the accuracy of the calculation of RF-induced tissue heating. This study analyzes the predicted RF-induced tissue heating at the tip electrode due to variation in lead insulation thickness for a pacemaker lead. RF-induced heating is characterized in three different TSMs, 0.47 S/m (body-average conductivity), 0.65 S/m (myocardium conductivity) and 1.20 S/m (blood conductivity). The simulations are compared with *in vitro* measurement for the nominal values of insulation thickness.

## II. METHODS

Numerical methods were used for estimating *in vitro* RF-induced heating for the lead model with varied insulation thickness. A pacemaker lead model of 45 cm in length was developed in Ansys HFSS, a commercially available full-wave computational electromagnetic software based on the finite element method. In the numerical simulations, the lead is exposed to a uniform plane wave and RF-induced tissue heating at the tip electrode is calculated. The lead insulation thickness is varied to study the effect on RF-induced tissue heating. The variability of RF-induced heating as a function of TSM is validated against measurement data in Fig. 1.

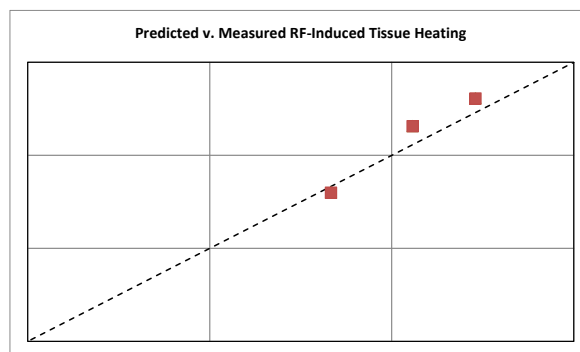


Fig. 1: Predicted v. measured RF-induced tissue heating near the electrode of a pacemaker lead for three conductivities of tissue simulating media.

## III. CONCLUSION

With the increase in lead insulation thickness, the RF-induced tissue heating at the tip electrode of the lead increases linearly up to a threshold thickness value (0.35 mm), afterwards a further increase in thickness doesn't affect predicted RF-induced tissue heating.

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J. E. Brown, P. Stadnik, L. Stotts, J. Von Arx, and K. N. Kurpad are with Micro Systems Engineering, Inc., Lake Oswego, OR 97035 USA (e-mail: james.brown@biotronik.com).

H. Kamineni is with Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843 USA.



# Computational study of model inaccuracy impact on dose estimation in TTFields therapy

Tal Marciano <sup>1\*</sup>, Oshrit Zeevi <sup>1</sup>, Zeev Bomzon <sup>1</sup>

**Abstract**— Tumor Treating Fields (TTFields) is a modality for treating Glioblastoma (GBM). A recent study combining clinical data and simulations demonstrated that the simulation-based dose estimation at the tumor level has a direct impact on the patient survival. This study opens the door to implementing computer-modelling based TTFields treatment planning in the clinic. Performing such planning in a meaningful manner requires an understanding about how inaccuracies in the patient model influence calculated TTFields distributions. In this study we show the effect of local perturbations in the model, errors in tumor segmentation as well and inaccuracy in the patient head's model on TTFields dose estimation.

## I. INTRODUCTION

Preclinical studies have demonstrated the relationship between the delivered intensity of TTFields to cells and the cytotoxicity [1]. A recent study based on extensive simulation performed on MRI databases from clinical trials have confirmed the preclinical observation at the patient level: higher dose at tumor level implies more survival [2].

The complexity of the head and its many tissues, brain circumplications as well as the uncertainty of the tissue's electrical properties, and boundary between tissues raise the question of the accuracy level needed to be achieved when creating a MRI-based phantom model for performing simulations. Related studies show differences when physicians perform manual segmentation of tissues [3]. The MRI image itself also has a certain level of inaccuracy compared to the patient's head. Therefore, there exist different levels of uncertainties, inaccuracies or assumptions related to model creation that can eventually impact our ability to accurately estimate the TTFields dose within the brain and tumor. In this study, we focus on two inaccuracy or uncertainty sources that impact the dose estimation. The first relates to local model uncertainties of a certain size and distance to the tumor. The second inaccuracy is the uncertainty of the tumor segmentation itself. We define sensitivity graphs enabling to estimate the potential inaccuracy of the dose calculation that such segmentation inaccuracy may lead to. Such results could serve as guidelines for model creation and tissue segmentation that would lead to optimal dose estimation in TTFields treatment planning.

## II. METHODS

Computational studies were performed with Sim4Life software.

\*email: [tmarciano@novocure.com](mailto:tmarciano@novocure.com)

<sup>1</sup>NOVOCURE LTD, Novocure, Topaz Building, 4<sup>th</sup> floor, MATAM Center, Sha'ar HaCarmel, Haifa 31905, Israel

## 1. Local model uncertainty outside the tumor region

To create defects in the models, conductive spheres with varying conductivities and radii were placed into the model's brains at different distances from the tumor. Virtual transducer arrays were placed on the models and delivery of TTFields numerically simulated. The error in the electric field induced by the defects as a function of defect conductivity, radius, and distance to tumor was investigated.

## 2. Tumor segmentation uncertainty

For illustrating segmentation errors in tumors and necrotic cores, layered spheres with various conductivities and radii where placed in different locations in the head. Tumor conductivity uncertainty was defined as:  $\frac{\sigma - \sigma_{ref}}{\sigma_{ref}}$ , where  $\sigma_{ref}=0.24$  S/m is the standard tumor conductivity and  $\sigma$  the varied conductivity over tumor. The normalized tumor radius was calculated when each of the varied radii was normalized to the results obtained by all the other combinations.

## III. RESULTS

Results show that that when a defect of radius R is placed at a distance, d, from the tumor that is larger than seven times R, the error is below 1% regardless of the defect conductivity.

The tumor segmentation uncertainty errors are represented in figure 1.

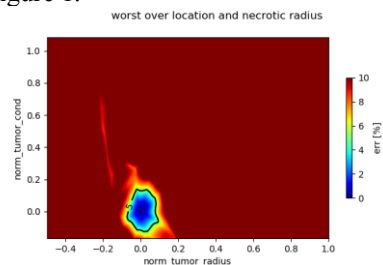


Figure 1. Error in dose estimation is indicated by the color bar as function of the tumor conductivity uncertainty and tumor radius uncertainty.

## IV. DISCUSSION & CONCLUSION

Our models and results show the impact of uncertainty in segmentation of the tumor and neighboring tissues on the TTFields dose estimation. They could serve as guidelines for performing accurate treatment planning of TTFields therapy.

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