

The Impact of Uncertainty in Nonlinear Temperature Dependent Constitutive Parameters on Predictive Computer Modeling of MRgLITT Procedures

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Introduction

MR guided Laser Induced Thermal Therapy (MRgLITT) for treatment of cancerous lesions in brain [1] as well as neurological disease presents an attractive treatment option with less morbidity compared to conventional surgical procedures. Multiple post market studies are currently on-going for FDA cleared MRgLITT devices. MRgLITT systems incorporate real-time MR temperature imaging (MRTI) and dosimetry to provide real-time feedback, thus making MRgLITT procedures safe and feasible. In view of the recent computational progress made in medical imaging, significant efforts are ongoing to incorporate predictive prospective computer simulation integrated with 3D visualization and assessment of diagnostic and interventional MR imaging information.

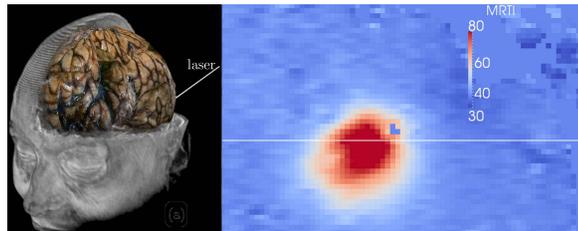


Figure 1. MRgLITT Setup and MRTI in Brain

Truly predictive prospective computer modeling requires substantial validation efforts and novel computer modeling techniques that incorporate the uncertainty of the input of computer model parameters into the predicted solution. A common method for predictive modeling of the distribution of induced heating in perfused tissue is the Pennes bioheat transfer equation (BHTE) [2] solved with a finite element method (FEM) [3]. A difficulty in obtaining accurate results from the BHTE is the uncertainty incurred by using assumed constitutive values, such as tissue heat conductivity, and perfusion as well as optical absorption and scattering parameters. Here we investigate the use of a stochastic BHTE where temperature dependent constitutive values are described via an assumed probability distribution providing the ability to perform uncertainty quantification (UQ) [4] of the output temperature and damage for each location at each time point.

Statistical methods provided by the UQ techniques provide novel methodologies for modeling the complex bioheat transfer phenomena. In particular, it is well known that the constitutive parameters behave nonlinearly with temperature increase and tissue damage. Constitutive parameters that account for damage dependent nonlinearities of the perfusion, thermal conductivity, and optical parameters [5] are generally more scarce than the linear counter parts and the variability seen within the literature indicates a higher degree of uncertainty within the nonlinear parameters [6]. Within the probabilistic setting of UQ, the range of constitutive nonlinearities may be modeled through the uncertainty within the linear UQ problem. This novel modeling techniques facilitates a substantial increase in compute efficiency and maintains computer modeling predictability by incorporating the advanced bioheat transfer phenomena.

Methods

Retrospective analysis of MRTI data from a clinical MRgLITT procedure in brain was performed. A diagram of the setup is shown in Figure 1. A patient with a recurrent glioblastoma was exposed to a 980-nm laser irradiation (4W and 10W for $\leq 140s$) using a 1 cm diffusing-tip fiber encased in an actively cooled sheath (BioTex, Inc, Houston, TX). The catheter was positioned under MR guidance into the right frontal lobe. Imaging was performed on a 1.5T whole body scanner (Espree, Siemens Medical Solutions, Erlangen, Germany) with an 8-channel, phased-array head coil (Noras MRI Products, GmbH, Germany). Exposures were monitored in real-time using the temperature-sensitive proton resonance frequency (PRF) shift technique via a gradient spoiled, two-dimensional fast low angle show sequence which generated temperature measurements, every 5 sec (TR/TE/FA = 38 ms/20 ms/30°, frequency x phase = 256 x 128, FOV = 26 cm², BW = 100Hz/pixel). An uncorrelated Gaussian measurement model was assumed for the PRF-based MR thermal image measurements (SNR ≥ 10). Representative MRTI at a time point of maximum heating is shown in °C, Figure 1.

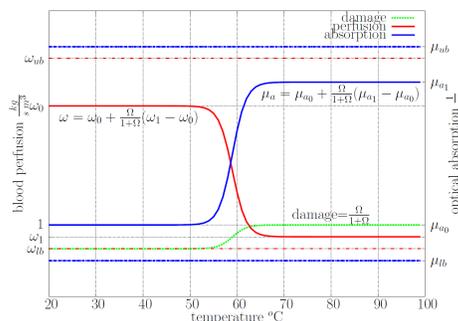


Figure 2. Constitutive Parameter Nonlinear Models

Computer simulations use generalized polynomial chaos (gPC) methods to provide UQ in the output variables variables [4]. Conductivity, perfusion, optical absorption, and optical scattering for the linear problem were considered and uniform random variables were taken from the physically meaningful range of literature values [5–7]. Temperature dependent nonlinear parameters for the perfusion and optical absorption were also considered as seen in Figure 2. Computational resources were provided by The University of Texas at Austin’s Texas Advanced Computing Center’s supercomputer, Ranger (579.4 TFlops, 123 TB memory). The FEM mesh was built in Cubit (Sandia NL). The visualization was created in ParaView (Kitware). The UQ was executed by DAKOTA (Sandia NL).

Results

Figure 3 displays spatial profiles comparing experimentally measured temperature values and UQ simulations with and without constitutive nonlinearities. The profile location is shown in Figure 1. The 95% confidence interval for the linear UQ simulation is shown to encompass the nonlinear simulation. The confidence intervals of probable temperatures from the model and MRTI are overlapping.

Discussion

The variability observed in the nonlinear computer models is seen to be encompassed within the linear UQ computer models. Hence within a probabilistic sense, the linear UQ simulations may potentially serve as a computationally efficient and predictive surrogate to the nonlinear UQ simulations. However, smaller variability is seen within the nonlinear UQ simulations. Work on a statistically significant amount of patient data is ongoing and is being used to critically evaluate potential prospective treatment time decisions from the confidence intervals provide by linear and nonlinear UQ simulations.

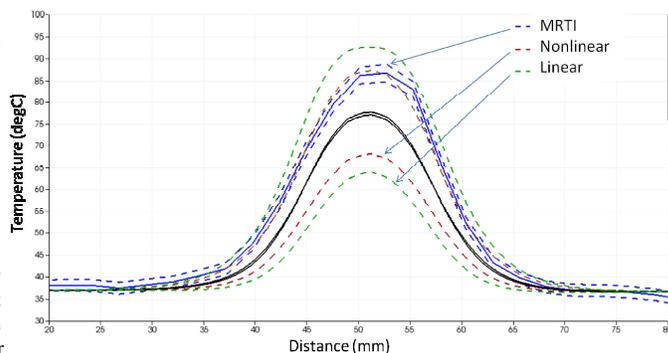


Figure 3. Spatial Profile

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References

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