Real-Time Bioheat Transfer Models for Computer Driven MR guided LITT

D. Fuentes[1], Y. Feng[2], A. Elliott[1], A. Shetty[1], R. McNichols[3], J. T. Oden[4], and R. J. Stafford[1]
[1]Imaging Physics, The University of Texas MD Anderson Cancer Center, Houston, TX, United States, [2]The University of Texas at San Antonio, [3]BioTex Inc, [4]ICES, The University of Texas at Austin

Introduction:
Treatment times of computationally assisted MR guided laser induced thermal therapies (MRgLITT) are determined by the convergence behavior of PDE constrained optimization problems. This work investigates the feasibility of applying real-time bioheat transfer constrained model calibration to patient specific data and rigorously validates model calibrations against MR temperature imaging data. The calibration techniques attempt to adaptively recover the patient specific bio-thermal heterogeneities within the tissue and result in a formidable PDE constrained optimization problem to be solved in real time. The heterogeneities are mathematically represented by thousands of model parameters and have been shown to deliver model predictions of unprecedented accuracy [1]. The calibrations are critical to the predictive power of the simulation during therapy which may be further exploited for treatment optimization to maximize the efficiency of the therapy control loop.

Methods:
An in vivo MR-guided LITT experiment was performed in a canine prostate model. Handling of the canine was in accordance with an Institutional approved protocol. General anesthesia was induced utilizing meditomidine (0.5 mg/kg, intramuscular) and 2% isoflurane was used to maintain general anesthesia throughout the duration of the experiment. The experimental configuration for the calibration study is illustrated in Figure 1. A clinical 1.5-T MR scanner (Excite HD, GEHT, Waukesha, WI) equipped with high-performance gradients (40 mT/m maximum amplitude and 150 T/m/s maximum slew rate) and fast receiver hardware (bandwidth, +-500 MHz) was used to acquired all images. A stainless steel stylet was used for inserting the laser catheter, 400 micron core diameter silica fiber in a water-cooled diffused tip catheter (Visualase Inc. Houston, TX). Planning images were acquired and used to guide the position of the laser fiber. Under real-time proton resonance frequency (PRF) based multiplanar MR temperature monitoring (EPI Sequence, FA= 60o, FOV= 24x24cm, slice thickness 4.0mm, TR/TE=544/15 ms with 5 sec per update), a region of the prostate of the anesthetized canine was heated with a non-destructive test pulse from the interstitial laser fiber (980nm; 5 Watts for 60 seconds) housed in an actively cooled applicator. The multiplanar thermal image data is projected onto a finite element representation of the prostate and used to calibrate a model of the bioheat transfer; the space-time norm of the difference between the in vivo MR temperature field and the predicted temperature field is the objective function to be minimized over the set of thermal parameters. The optical-thermal response to the laser source is modeled as the classical spherically symmetric isotropic solution to the transport equation of light within a laser-irradiated tissue [2] coupled to the Pennes bioheat equation. The perfusion and thermal conductivities are recovered from the calibration computation. An adjoint method is used to compute the gradient of the objective function to drive the quasi-Newton optimization algorithm.

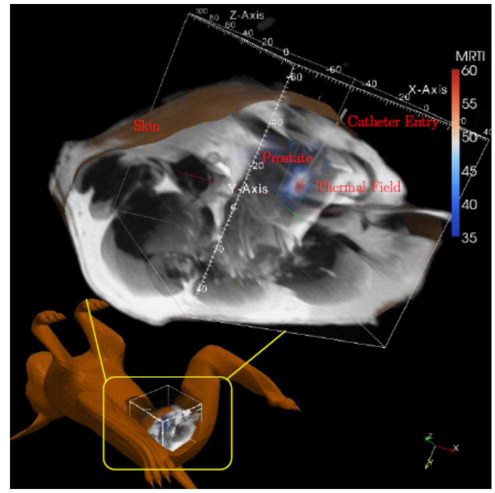

Figure 1. Experimental Setup.

Results:
Results of a comprehensive calibration study with both homogeneous and spatially heterogeneous bio-thermal model parameters with and without constitutive nonlinearities indicate that the calibration problems involving the inverse solution of thousands of model parameters can converge to a solution within three minutes and decrease the space time norm of the difference between computational prediction and the measured MR temperature values to a patient specific regime. Figure 2 illustrates the effect of the calibration. As expected from an isotopic source, the model prediction with homogeneous coefficients is seen to create spherical isotherms. Model predictions with heterogeneous coefficients are seen able to recapitulate the structure of the isotherms in the thermal imaging data. Pointwise error between the calibrated model and the thermal imaging is on the order of the noise in the thermal imaging data; the average standard deviation of pre-heating thermal images measured in a 5 x 5 x 5 pixel ROI within the contra-lateral lobe of the prostate was 1.53^{o}C The calibration study was furthered to investigate effects of the thermal imaging data time window used in the objective function. The time intervals were chosen to study the effect of using the heating phase, the heating and cooling of the in vivo, and attempts to eliminate the laser source and account only for the cooling of the tissue. Results indicate that using a data interval of 1.5 times the duration of the calibration pulse is optimal in terms of computation efficiency, ie provides the greatest objective function decrease for the least amount of computational work. Finally, the observed objective function convergence history for selected calibration problems of the study is presented in Figure 3. The graph is intended to convey the general convergence behavior of the breadth of the calibration problems studied. The PDE constrained optimization problems are seen to converge to their minimum within an average of 20 function evaluations.

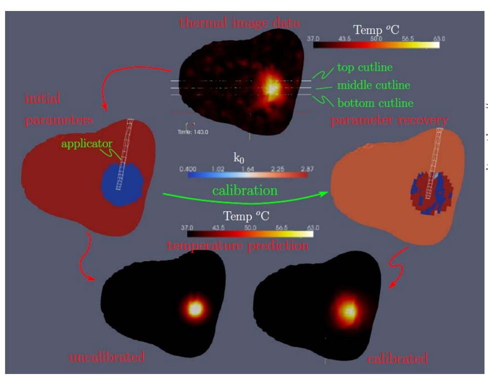

Figure 2. Model Calibration.

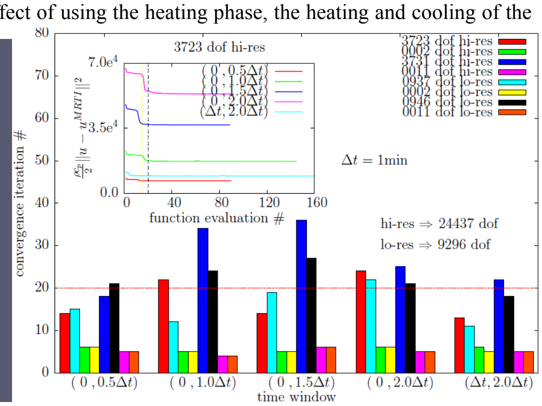

Figure 3. Calibration Convergence.

Conclusions:
Results demonstrate that a calibration pulse prior to MRgLITT can be used to substantially increase modeling accuracy for delivery prediction. Calibration of the model based on accounting for spatial heterogeneities in the tissue produce much greater improvements in predicted temperature than upgrading terms in nonlinear constitutive equations. This suggests an effective constitutive alternative to modeling the nonlinear bioheat transfer observed in soft tissue. The tissue behaves as a heterogeneous but linearly conductive media. Results also indicate the existence of a critical time interval of the calibration objective function beyond which further use of data provides diminishing returns. We hope that these results help guide independent in vivo experiments and translational research on the path to realizing the model calibration aspect of computer guided LITT technology within a clinical setting.

References:
1. **Diller, K.R., et al., *Computational Infrastructure for the Real-Time Patient-Specific Treatment of Cancer*, in *Advances in Numerical Heat Transfer*, W.J. Minkowycz and E.M. Sparrow, Editors. 2008, Taylor & Francis Group.**
2. **Welch, A.J., et al., *Optical thermal response of laser-irradiated tissue.* New York, 1995.**