MRI monitoring and Mathematical Modeling to Predict Tissue Lesion Size from Laser Thermal Ablation

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Objectives: The objective of this study is to validate a mathematical model for predicting the **thermal lesion size in tissue** during MR-guided laser thermal ablation (LTA). A mathematical model is useful in providing an accurate lesion size for a given temperature and duration of ablation in a particular tissue. For this purpose, we 1) evaluated the rapid MRI assessment of tissue lesion size via LTA in rabbit paraspinal muscle, 2) correlated model-based computer simulations with lesion size documented by histopathology, with MR temperature and magnitude images 3) compared simulated lesion size to that obtained in tissue with and without a tumor and 4) compared the mathematical model to temperature maps obtained from MR images.

Materials and methods: LTA was performed in the paraspinal muscle of 10 rabbits with and without a VX-2 tumor approximately three weeks after local cell injection. Tissue heating was produced using an Nd-Yag laser placed under MR guidance. The laser fiber connected to a diffuser tip was surrounded by a cooling catheter. MR slices obtained with a GRE sequence (TR/TE/θ = 26 ms/13 ms/14°; NSA 1; FOV 275 mm x 137.5 mm; Matrix 256x128; Slice thickness 5 mm), were acquired in 3.3s every 10s during heating and cooling. The lesion boundary was manually segmented from the magnitude GRE images. After euthanasia, muscle specimens were collected to document the lesion size and characteristics by histopathology. Prediction of the lesion area dynamics was obtained with a thermal model similar to that of Chen et al. [1]. This model included a tissue damage analysis as validated by Breen et al. [2] which was compared to the time series of MR images.

Results: Position of the laser heat source is shown in the center of the lesion as a larger dark point (Fig. 1). The smaller point seen indicated the position of optical temperature sensor (Luxtron One) used to provide a reference measurement. GRE magnitude images show the lesion development (Fig.1). Each segmented lesion area is plotted as a function of time and fits tissue damage model prediction (Fig 2) within about 1 mm actual histologic data. From the mathematical model, region I is where the tissue is absorbing heat without showing the lesion due to cooling from blood perfusion. Region II demonstrates lesion growth as a function of time and III shows lesion growth in the post-ablation state due to the accumulated temperature history. Two heat source models were used for comparison: one was a simplified model from an infinite cylindrical light source and the other was numerically calculated from photon diffusion and updated to the tissue damage status. Parameters are estimated from lesion area predictions per Table 1.

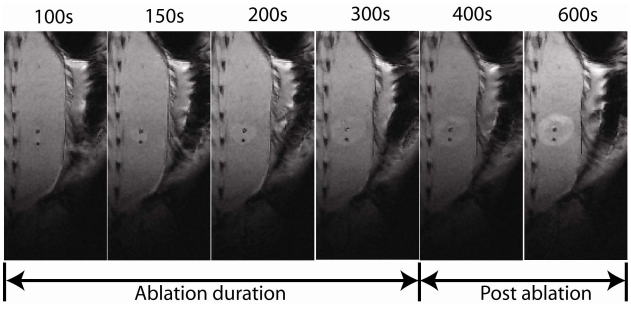

Fig 1.Dynamic lesion growth in normal tissue.

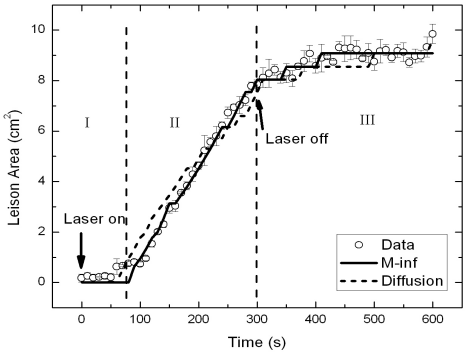

Fig.2. Mathematical model fits lesion area. (o): Data segmented from (a), (-) modified heat source from infinitely long cylindrical laser heat source, (- -) heat source numerically obtained from photon diffusion.

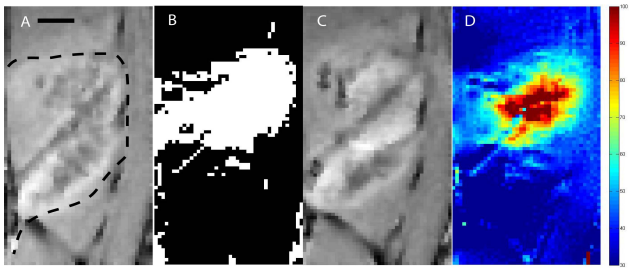

Fig.3. A: pre-ablation GRE magnitude image (dashed line: tumor boundary), B: lesion boundary computed in white area ($P_D^{thr} \le P_D$) C: post-ablation GRE magnitude image, D: temperature map at the end of heating. Bar: 10mm

Parameters	$avg \pm \sigma$
$\beta_0\ (\times 10^{-3} s^{-1} \cdot^o C^{-1})$	1.03 ± 0.08
P_D^{thr} (%)	0.78 ± 0.07

Table1. Tissue damage parameters estimated from normal tissue results.

LTA was performed on tumor tissue as shown in Fig 3 with 6min of ablation time and cooling time each. GRE pre- and post-ablation images are shown in Fig 3 A and C. Hyper-intense area indicates the lesion at the end of cooling period in Fig 3 C. Time-dependent temperature maps were used to compute the lesion boundary from Fig 3B by the equation in Table 1. The temperature map (t=360 s) is shown in Fig 3D.

Conclusion: The mathematical model of Laser Thermal Ablation showed higher accuracy for lesion size in normal paraspinal muscles when a real time MR guided ablation was performed. The ablation zone determined by histological examination validated our mathematical model, which when tested in VX-2 tumors in the paraspinal muscles, gave equally well- correlated results. To our knowledge, this is the first study in which mathematical predictive models of cell death are incorporated with real time MRI LTA trials.

References:[1] Chen X, et al. JMRI 2007; 26(1):123-32. [2] Breen MS, et al. Ann Biomed Eng 2007; 35(8):1391-403. [3] Anzai Y, et al. JMRI 1991; 1(5):553-9.