FAST PREOPERATIVE PLANNING METHOD FOR MR-GUIDED LASER ABLATION IN BRAIN

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Introduction: MRI-guided laser ablation of brain tumors is being investigated as a minimally invasive treatment option that brings potential reductions in procedural morbidity, complications and overall cost compared to conventional surgery. Akin to biopsy[1], previously acquired MR images are usually used in conjunction with framed or frameless stereotactic guidance to navigate the laser applicator(s) through a keyhole in the skull to the target. MR temperature imaging (MRTI) provides quantitative periprocedural monitoring of the temperature changes in the volume of interest during therapy delivery[2]. While several vendors have hardware coming to market for these procedures, there is still need for fast, user friendly software approaches for simulation and visualization of the possible outcomes of complex treatment scenarios (e.g., multiple applicators/trajectories with convective boundaries in heterogeneous tissue) in order to rigorously assess feasibility of therapy. In this research, we introduce a portable, 3D image-driven method and graphical user interface (GUI) for prospective treatment planning of laser ablations in brain. The open-source software can simulate biothermal distribution and expected tissue damage and facilitate virtual adjustment of laser applicator(s) position/power relative to 3D anatomy and visible boundary conditions, to rapidly evaluate the feasibility of different treatment scenarios. Prediction accuracy of the proposed system was critically evaluated using retrospective analysis of human studies.

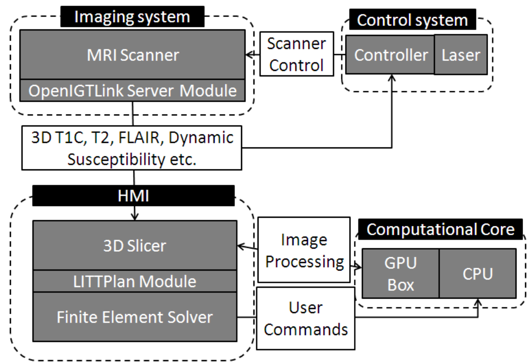

Fig. 1: System Architecture and workflow.

Methods: The system has four major components as illustrated in Figure 1. A Human Machine Interface (HMI) was built around an open-source[3] platform ('LITTPlan' module in 3D Slicer version 4.1) which obtains images directly from the scanner using custom software based on OpenIGTLink, which offers a standardized mechanism for data exchange between different hardware and software components of such systems[4]. 3D Slicer is a multi-platform, extendible and open-source software system that provides immense functionality for highly demanding 3D visualization, registration and segmentation tasks as well as image-guidance software implementation tools. LITTPlan was developed in-house to provide an intuitive and information-rich virtual environment, which enables the operator to interact with 3D models based on preoperative MR images, create a navigation path and locate laser applicator at a desired target with mouse clicks. Then he/she can set the treatment parameters such as, laser power, temperature isotherms to be simulated and different tissue parameters (i.e., thermal conductivity, tissue perfusion, optical absorption, scattering and anisotropy), which are set to the literature values for each tissue type by default (Figure 2). As the first step of image processing, target treatment volume and critical structures (e.g., grey/white matter, edema, tumor etc) are segmented from patients` baseline MRI and potential convective heat sinks such as nearby vessels and ventricles etc. are identified. A steady-state finite element solver is used for simulating the induced heating and expected tissue damage results (i.e., isotherms) of different heating scenarios based on above parameters. To achieve very fast simulation an optimized computational model, linear Pennes Bioheat Equation was adapted. Temperature was calculated and resulting isotherm estimates of damage were registered as overlays on the treatment planning images. Those simulations then tested for accuracy via retrospective analysis of human MRTI data from laser ablations in brain (N=5) using a 980-nm laser (Visualase, Inc.).

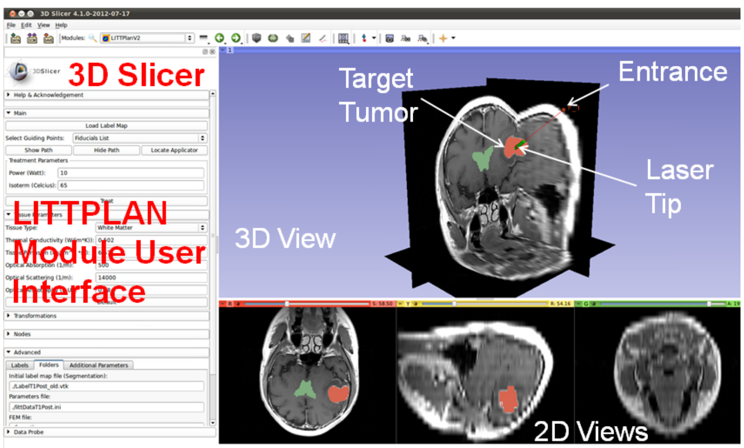

Fig. 2: 3D Slicer and LITTPlan graphical user interface for planning the procedure.

Results and Conclusions: Five human subjects were treated with laser induced brain tumor ablation under 1.5T MRI Scanner (GE Healthcare). The pretreatment MRI data were loaded to LITTPlan and steady-state simulation was run for each with the same applied laser power of 10 Watts. The simulations for each treatment were able to calculate isotherm estimates and provide simultaneous visualization of the MR planning images, segmentations of critical structures, and thermal dose estimates to the operator in less than 20 s. The simulation results were compared to MRTI output saved during the procedures at the highest temperature timepoint. As shown in Figure 3, the temperature profiles were plotted along two lines, LX and LY, parallel to X and Y axes respectively using free software tool ParaView (Kitware, Inc). The ablation started when the tissue temperature reached ~42 °C, and maximized at ~57 °C (and above). Given the short duration of laser heating in this scenario (<180 s), a 57°C isotherm can adequately capture damage accrual. The simulations calculated this damage (i.e., 57 °C isotherm) with mean distal error of 3 mm in any direction on the registration plane, whereas the mean difference between calculated and measured temperatures was 4°C for any given point. These minor errors can be due to segmentation and registration inaccuracies as well as the expected uncertainty (e.g., from probe location, fluence, convective or conductive properties).The presented efforts demonstrate the feasibility of incorporating MR-based predictions of bioheat transfer into an interactive virtual planning environment in near-real-time. The 3D environment for planning the procedure presents opportunities for patient selection and optimizing treatment approach as well as integration with established neuronavigation systems such as Brainsuite (BrainLAB, Inc) via IGTLink. Our immediate future work includes incorporating an uncertainty quantification formalism to provide a confidence interval for the results. The uncertainty in the model will be propagated such that uncertainty in both temperature and damage can be quantified and displayed to enhance the interpretation of simulations.

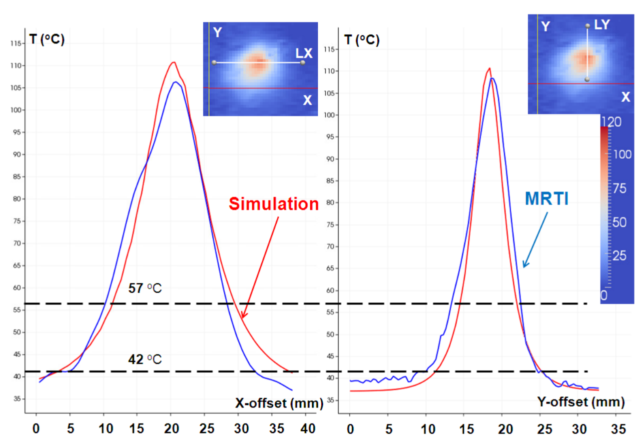

Fig. 3: Simulation (red) vs. MRTI (blue) on the time-step with the highest temperatures along the white lines parallel to X and Y axes respectively.

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