3D Model Characterization of Brain Tissue Damage in Magnetic Resonance-guided Laser Interstitial Thermal Therapy via a Computational Algorithm in MATLAB

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Introduction
Magnetic Resonance-guided Laser Interstitial Thermal Therapy (MRgLITT) is a minimally invasive approach for focal ablation of difficult-to-treat intracranial pathologies. Using the Visualase Thermal Therapy System (Medtronic Inc, Dublin, Ireland), laser energy is administered via a pre-planned catheter trajectory while actively monitoring both heat distribution and thermal damage estimate (TDE) in two orthogonal MRI planes for one procedure. Previous analyses of intraoperative MRgLITT data has measured TDE surface areas (SA) and demonstrated a strong correlation to postoperative MRI ablation SA estimates. However, these past studies have been limited in scope due to the minimal intraoperative 2D data for 3D laser ablations.

Objective
Present a computational algorithm that utilizes orthogonal TDE cross-sections to estimate brain damage volumes from MRgLITT.

Methods

General Mathematical Approach
Using TDE dimensional parameters from the two perpendicular MRI scans of a MRgLITT procedure, the TDE volume was calculated via the “known cross-section definite integral method. First, the axes that the two TDE images are orthogonal to each other were determined by identifying the laser trajectory. Based on the well-documented spherical-nature of ablations, TDEs were characterized as ellipses. For one MRI image (assigned to spatial YZ coordinates), major axes length was identified as the span of the TDE in-line with the laser path. Two minor axes lengths (“width”) were identified at the perpendicular axis intersecting the TDE center and represented the “top” and “bottom” halves of the TDE. Major-minor axes ratios were calculated. For the second MRI image (assigned to XY coordinates), the TDE was divided into quadrants to calculate four standard ellipse equations. Because the laser path is along the axis intersecting the first MRI image, the major axes length is the same as the first analyzed TDE for all equations. Minor axes lengths were solved using the ellipse equation, the known major axes length, and a TDE edge point (x,y) identified at the midline of each quadrant. A definite integral is applied across an X-axis interval using the ellipse area formula (π * minor axis * major axis) as a function of X to approximate the missing cross-sections modeled from YZ axis TDE slice. Across the interval, the major axis was calculated using the previously identified XY TDE ellipse equations. The minor axis was calculated using the “top” and “bottom” axes ratios of the YZ TDE slice. This approach is summarized in the shown simplified mathematical equations (Figure 2).

Algorithmic Implementation
A semi-automated algorithm was developed in MATLAB to apply our definite integral approach. First, the user crops the TDE from the orthogonal MRI slices, and second, the laser trajectory is identified by two user click-points. Before further pre-processing, to keep track of this trajectory, the TDE edge point in line to the laser path was transformed to a red pixel to become a counter point. Finally, both TDE slices were rotated for the laser path to be positioned on the image’s center axis. These resulting TDEs are then used to implement our mathematical approach to solve for volume (Figure 1).

Post-ablation volumetric measurements.
Using full axial MRI scans obtained immediate post-operative (IPO) and post-24 hours (hrs), two blinded raters computed volumes via the “pencil tool” in Osirix (Pixeo Inc, Bernex, Switzerland). These volumes were compared to our algorithmic calculations via ANOVA.

Results
5 MRgLITT patients with lesions at least 1 cm from convexity were included. No significant differences by t-tests were observed between raters’ volumes for IPO (P = 0.90) and post-24 hrs (P = 0.80). For algorithmic evaluation, IPO, and post-24 hours, average ablation volumes (cm^3) were 3.8 ± 1.1, 4.0 ± 1.1, and 4.8 ± 1.2, respectively. No significant differences were detected by ANOVA (F = 3.58, P = 0.13, R^2 = 0.47).

Conclusion
Preliminary analyses demonstrate the feasibility of our algorithm to predict ablation volumes. We are currently increasing our patient cohort to further validate and improve our algorithm. Overall, our computational method will aid surgeons to efficiently measure the success of full ablation of a target brain lesion and provide insight into future laser catheter pre-planning.

Figure 1. (A) Original intraoperative MRgLITT image. (B) MATLAB algorithmic pre-processing of the two orthogonal TDEs in the original image. (C) TDEs superimposed with each other on a 3D axis with final volume reported.

Figure 2. Simplified mathematical equations for the known-cross section definite integral method to calculate TDE volumes.