Treating Epilepsy via Thermal Ablation: Initial Experiments with an MRI-Guided Concentric Tube Robot

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1 Background

Epilepsy is a prevalent neurological disorder affecting 65 million people globally [1]. Anti-epileptic medications fail to provide effective seizure control for 30% of patients, placing them at a 7-17% risk of Sudden Unexplained Death in Epilepsy and recurrent seizures. Surgical resection of the seizure focus is a potentially curative treatment for patients with seizures that electrophysiologically correlate to a focal lesion. For these patients, focal surgical resection can result in 60-70% seizure-freedom rates [2]. However, open resection carries the risk of cognitive impairment or focal neurologic deficit [3].

Recent innovations in MRI enable high resolution soft tissue visualization, and real-time temperature monitoring, making MR-guided ablation therapy a promising minimally invasive technique to restrict the tissue destruction to just the seizure focus. Commercial products (e.g., Visualase, Medtronic Inc.; ClearPoint, MRI Interventions Inc.; NeuroBlate, Monteris Inc.) have recently been introduced for MR-guided laser-based thermal ablation. These products require the physician drill a hole into the skull for ablation probe placement, and may not always be able to ablate the entire seizure focus when the structure has a curved shape (such as the hippocampus) [4]. Incomplete ablation of the seizure focus could lead to seizure recurrence.

We have recently proposed concentric-tube steerable needles as a means to address these challenges [4-7]. They enable nonlinear trajectories and offer the potential to enter the brain through the patient’s cheek via a natural opening in the skull base (i.e. the foramen ovale). We have designed and fabricated an MR-compatible robotic system to provide high resolution actuation for helical needle deployment [5]. We have shown in simulation that the curved medial axis of the hippocampus can be accessed via a helical needle that delivers the ablation probe into the brain [4]. These preliminary results suggest that MR-guided robotic transformamal thermal therapy could potentially provide a less invasive approach for potentially curative epilepsy treatment. In this paper we present our first results delivering heat along curved paths in brain phantoms and imaging the resulting treatment zones using MRI.

2 Methods

The experimental setup used to deliver the helical concentric tube robot and radiofrequency (RF) ablation probe is shown in Figure 1A. As in [4-7], it includes an outer straight stiff nitinol delivery tube (OD: 2.4mm, ID: 1.9mm) that reaches up to the foramen ovale, a middle flexible helical nitinol tube (OD: 1.4mm, ID: 0.9mm) that enters the brain, and a flexible, straight custom-made RF ablation probe (OD: 0.8mm) made from a nitinol wire shielded via heat-shrinkable PTFE tubing. A straight sheath of thin-wall nitinol surrounds the insulation at all times and prevents it from being damaged as the ablation probe slides in and out of the helical tube. The helical tube was set into its shape using the electrical shape setting technique of [8]. As described in [6], we used a screw based mechanism (Figure 1B) matched to the helical tube’s shape to deploy it in a “corkscrew-like” follow-the-leader trajectory.

![Figure 1](image.png)

Figure 1 (A) Helical RF ablation probe. l is the linear ablation probe insertion depth; (B) Experimental setup for the RF ablation test.

The ablation probe was wired to an RF generator (Vulcan, Smith & Nephew Inc.) and tested in a temperature sensitive agar phantom (water: 60%; egg white: 37%; agar: 3%). The experimental setup is shown in Figure 1B. Using the generator’s coagulation mode with a temperature setting of 60°C for 5 sec resulted in an ablation zone diameter of 4mm. Note that larger ablation diameters can be created with alternate generator settings, and 1cm is easily achievable. After performing ablations on the benchtop, the ablated phantom was transferred to the MRI scanner for image-based evaluation of the ablation zone. Two different scenarios with different RF probe insertion depths were performed, as described in the following section. The ablation volume was segmented with 3D Slicer and compared with model-based predictions of the trajectory curve.

3 Results

Figures 2 and 3 show the ablation results with the proposed helical ablation system. The predicted trajectory was...
based on the ablation probe insertion depth and the helical needle parameters: radius (4mm) and pitch (61.5mm).

Figure 2 Trajectory 1: (A-B) helical lesion in two slices; (C) the segmented ablation volume (blue points) registered to the planned trajectory (cyan curve). The black dashed curve indicates the medial axis of the ablation zone. Error: max = 1.6mm, mean = 0.7mm, min = 0.03mm.

Figure 3 Trajectory 2: (A) The helical trajectory entering and exiting an image slice; (B) the linear portion of the trajectory; (C) the segmented ablation volume (blue points) registered to the planned trajectory (cyan curve: helical ablation; magenta line: linear ablation). The black dashed curve indicates the medial axis of the ablation zone. Error: max = 0.76mm, mean = 0.47mm, min = 0.14mm.

Two insertion trajectories were experimentally tested. The first (Figure 2) evaluated a pure helical trajectory. The second evaluated a combination of an initial helical trajectory and a subsequent linear trajectory of the ablation probe (Figure 3). In both scenarios, sequential ablations were applied every 3mm along the trajectory, leading to a tubular ablation zone along the needle trajectory. The arc length of the first trajectory (Figure 2) was 55mm. The helical arc length of the second trajectory (Figure 3) was 24mm and the straight deployment length of the ablation probe was \( l = 20\text{mm} \). Ablation profiles along the needle trajectory were selected in keeping with the concept introduced in [4-6], in which the needle is delivered as nearly as possible along the medial axis of the hippocampus and delivers thermal energy radially in all directions along its path.

Scenario one was performed in a 3T MRI, and scenario two was in a higher resolution 4.7T MRI scanner, simply due to scheduling availability of the two machines. To evaluate accuracy in both scenarios, we defined error as the distance between each point on our predicted trajectory and its closest neighbor in the medial axis of the ablation zone after registration. Both trajectories resulted in sub-millimeter accuracy as given in the respective figure captions.

4 Interpretation

This paper presents our first experiments on delivering thermal ablation using our helical steerable needle system and imaging the resulting ablation zone using the MRI scanner. Experimental results show that the ablation volume can be predicted based on needle geometry. Future work will focus on MR-guided robotic ablation of specific target zones in ex-vivo animal tissues.

References