Robotic Curvilinear Laser Thermal Therapy Probe for Transforamenal Hippocampotomy

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INTRODUCTION

Epilepsy affects an estimated one out of 150 people, with 30% of patients unresponsive to existing drug-based therapies for seizure management. Hippocampal resection can be a curative procedure for drug-resistant temporal lobe epilepsy [1], however, current rates of surgical resection are limited by perceived and real risks of undergoing neurosurgery [2].

Laser Interstitial Thermal Therapy (LITT) is a less invasive alternative to surgical resection, which heats brain tissue causing thermal necrosis [3]. Existing commercial LITT tools (Medtronic, Monteris) are straight probes which are inserted through the skull. Reaching deep brain targets such as the hippocampus requires traversing significant amounts of potentially eloquent brain tissue [3]. Deploying LITT using curved needles to avoid critical neural structures has been proposed and explored in simulation and computational design [4], [5], but has yet to be demonstrated experimentally. The purpose of this paper is to describe the first experimental prototype of a needle that can deliver LITT along a curved trajectory.

MATERIALS AND METHODS

Our novel approach to LITT delivery to the hippocampus through the foramen ovale is shown in Fig. 1a. A helical needle with a curvature of $\kappa = 47.14 ^1/_m$ and a torsion of $\tau = 80.95 ^{rad}/_m$ was fabricated by shapesetting a .045" OD / .039" ID nitinol tube. Design parameters for the helical needle were determined using a path planning optimization technique described in [5]. The highest curvature patient-specific needle from that study is used here, since it represents the greatest potential for optical bend losses. A 200μm, bend insensitive multimode fiber (Newport MKS: F-MBB) was integrated into the helical needle to form the curvilinear laser delivery probe, which was powered by a 15W, 980nm clinical laser (BW Tek: BWF5-980-15).

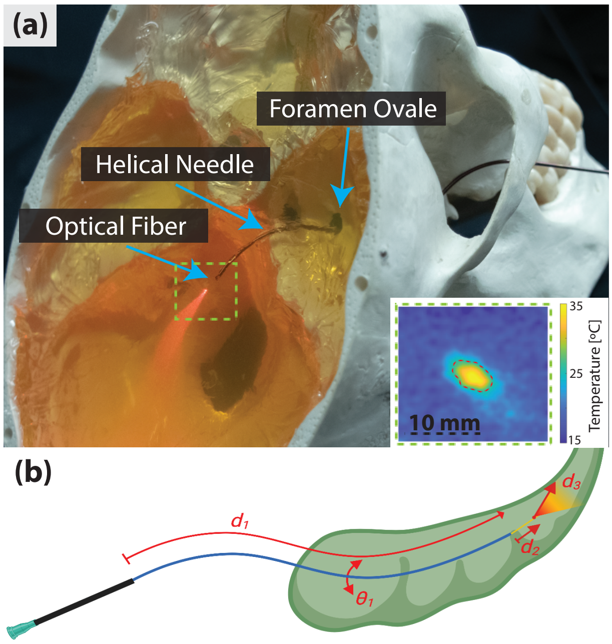

Fig. 1 (a) Helical needle delivered through the foramen ovale in a skull model filled with gelatin; red laser indicating fiber output. Inset: Thermal image of gelatin phantom after irradiation. (b) LITT delivery system degrees of freedom.

The probe was delivered using a pneumatically driven MR-compatible robot, described in [6] using a follow-the-leader approach. Our robot degrees of freedom are shown in Fig. 1b; d_1 and θ_1 are the translational and rotational pneumatically driven degrees of freedom of the helical needle, d_2 is the translation of the optical fiber out of the helical needle, and d_3 is the laser intensity, which affects the size of the treatment zone. The insertion DOFs (d_1,d_2) have a maximum travel of 120mm, while the laser can be controlled to create an ablation volume (d_3) of up to 15 mm in diameter. The pneumatic robot and laser were controlled using Simulink.

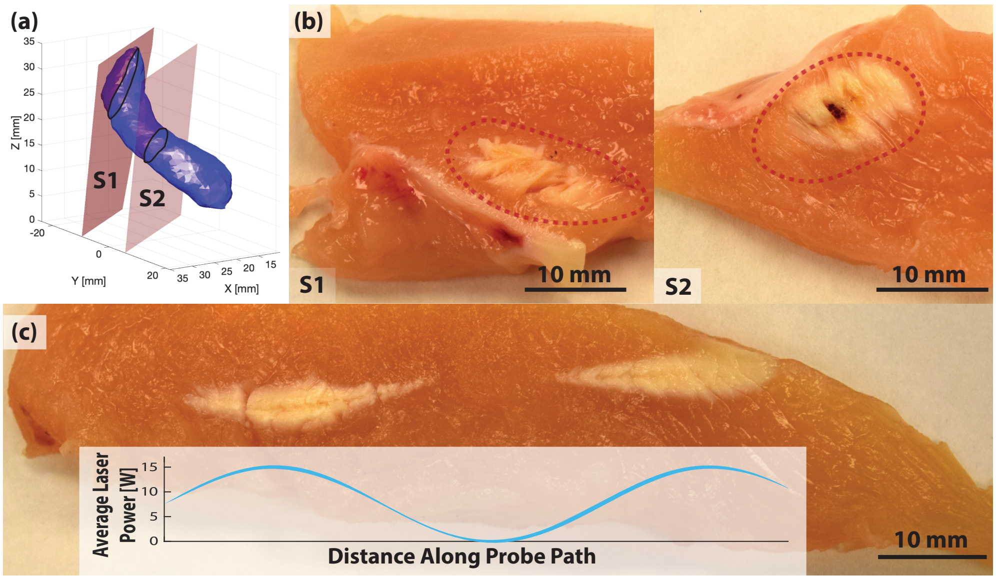

Fig. 2 (a) Segmentation of a human hippocampus from [5]. (b) Histology following ablation in chicken breast along a curvilinear trajectory matching the shape of the human hippocampus in a. (c) Modulating laser power with fixed translational speed to create a varying lesion diameter. (d) Helical path following demonstration.

RESULTS

The curvilinear laser ablation probe was first tested in a skull model filled with gelatin to demonstrate the ability of the helically curved needle to navigate through the facial-skeletal structures (Fig. 1a). A transverse view of the thermal treatment zone after irradiation with 3W for 30s was imaged using an IR-camera in the gelatin phantom. The dashed red line indicates a temperature rise of $> 10^{o}C$ above ambient temperature, which is an approximate threshold for thermal necrosis. The lesion size can be adjusted by varying the laser power or translation rate along the ablation path.

Subsequently, the curvilinear ablation probe was validated in *ex-vivo* chicken breast. The segmented MRI scan of a human hippocampus used to optimize the needle shape and trajectory is shown in Fig. 2a. The laser ablation probe was deployed 59 mm into ex-vivo chicken breast, and ablation was performed by robotically retracting the probe at a constant speed with incident power of 2.75 W for a duration of 11.5 min. Histological cross sections after the curvilinear ablation are shown in Fig. 2b, corresponding to approximate slices in the planned ablation volume in Fig. 2a. In Fig. 2c, we demonstrate the ability of the robotic system to create lesions with varying diameters; while the probe is translated through the tissue at a rate of 6 mm/s, the laser power is modulated sinusoidally over time. The ability for the needle tip to follow a helical path was confirmed using a magnetic tracker (Northern Digital) in Fig. 2d.

DISCUSSION

The integration of a curvilinear robotic delivery system with a laser therapy tool enables more precise thermal treatment zones due to the ability to control both path rates and laser power simultaneously to selectively ablation various lesion shapes and sizes, while navigating around anatomical constraints. We have demonstrated that with open-loop control of our robotic system, it is possible to ablate a volume of tissue that matches a pre-operative segmented MR scan of a hippocampus. To reduce the chance of tissue charring effects, we plan to integrate fluid or CO_2 cooling in future versions of the probe, and monitor tip temperature. We also plan to create an optical/thermal model to relate probe speed and laser power to the volume of necrotic tissue. Subsequently, the curvilinear LITT system will be integrated with real-time MRI thermometry for closed-loop control. This prototype combining curved needles and laser thermal therapy is a promising first step towards robotic LITT delivery for enhanced and targeting of deep brain structures using a minimally-invasive approach.

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