An MRI-Compatible Robot for Intracerebral Hemorrhage Removal

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1 Background

Intracerebral Hemorrhage (ICH) is the deadliest form of stroke and occurs when blood, leaked from a ruptured vessel pools in the brain forming a pool of semi-coagulated blood called a hematoma. 1 in 50 people will have an ICH in their lifetime [1] and the 30-day mortality rate is 43% with half of the deaths occurring in the acute phase, which motivates the need for safe and rapid treatment. However, literature reviews show no significant benefit of surgical removal vs. “watchful waiting”, despite the potential value of decompressing the brain. It has been hypothesized that this is due to the significant disruption of healthy brain tissue required to reach the hemorrhagic site in open brain surgery.

Recent studies conducted on phantom models have shown that a robotic needle made from curved, concentric, elastic tubes can reach a hemorrhagic site through a needle-sized path to successfully aspirate the hematoma. This approach has the potential to decompress the brain with far less disruption to surrounding brain tissue [4]. Those initial experiments were conducted under guidance from periodic (low rate) CT [2]. The need for intraoperative imaging was motivated by the fact that the brain shifts during aspiration, collapsing to fill the cavity left by voided blood. This approach has the potential advantage of “one stop shopping”, since ICH is typically diagnosed in the CT scanner. It is appealing to treat ICH immediately after diagnosis, while the patient is still in the scanner. However, CT also has the drawback of requiring ionizing radiation, as well as providing only intermittent images rather than real-time information.

In this paper, we consider a Magnetic Resonance Imaging (MRI) guided approach, which provides the converse in terms of both benefits and drawbacks. MRI is not typically used to diagnose ICH, but it can provide detailed soft-tissue and hematoma contrast [3], and fast image updates, enabling real-time monitoring of brain deformation during the aspiration process. Toward performing ICH aspiration with a concentric tube robot in an MRI environment, this paper presents accuracy and MR-compatibility tests for a new MR-compatible robot designed for ICH removal.

2 Methods

Our overall concept for a real-time MRI-guided system for ICH removal is shown in Figure 1A. It consists of a robot for actuating the concentric tubes, combined with an aiming device to initially point the robot in the desired direction. An active tracking marker, mounted at the tip of the aspiration tube, will provide intraoperative position feedback [4]. In the envisioned clinical workflow, the patient’s head is immobilized with respect to the MR scanner and robot with a head frame or clamp system. A safe entry path to the ICH is then specified by the neurosurgeon, the robot is aimed along this path by the aiming device, and the concentric tubes pass along the path and into the brain. Using the real-time MRI generated in the region of interest around the needle tip, the physician will be able to account for brain deformation and steer the needle to safely aspirate the hematoma from within.

The MRI-compatible ICH robot system (Figure 1B) consists of a biocompatible actuation unit and uses a mechanical design similar to that of [5], but different in that it is designed to be MRI-compatible. Each of the actuators (Figure 1C) is a novel type of pneumatic Pelton turbine motor, fabricated using a Stratasys Dimension SST 3D printer and equipped with a custom-made optical encoder enabling bi-directional encoding [6]. The robot is fabricated entirely with MRI-compatible materials, e.g. plastic, acrylic, brass, and aluminum, to ensure patient safety and image quality.

Figure 1: (A) Schematic diagram of MR-compatible ICH robot integrated with an aiming device inside the MRI scanner; (B) prototype of the MR-compatible robot. Left bottom inset shows a close-up of a steerable needle inside a blood clot phantom (red boundary). (C) MR-compatible motor coupled with a plastic gearbox.

To aim the steerable needle system at a hematoma in the brain, we designed an MR-compatible aiming device which can be seamlessly integrated with the ICH robot. This 2 degree-of-freedom (DoF) aiming device was inspired by the Leksell stereotactic frame. We tested the aiming device setup in 20 ICH models created using patient CT scans obtained from Vanderbilt University Medical Center. The robot was
able to reach, and cover with the concentric tube workspace, all of the ICHs in our 20 patient cases. We also performed MR Compatibility and accuracy tests on the robot.

3 Results

In this section we will evaluate the robot’s MRI-compatibility and needle tip positioning accuracy in detail. Figure 2 shows the experimental setup in the MRI scanner to evaluate the image artifacts at the region of interest. Image artifact is defined as 30% pixel intensity variation of bottle phantom [7] image when the robot is powered compared to the control image when robot is absent. No image artifact or distortion was observed in these two scenarios from Figure 3.

Figure 2: System setup in the MRI scanner. The robot is connected to the control box in the control room through 10-meter air hose and optical fibers.

Figure 3: T1 weighted MR image of the phantom when the robot is not in the scanner and when robot is in the scanner and powered on.

Needle tip positioning accuracy was evaluated in a separate set of benchtop experiments using a magnetic tracker (Aurora, Northern Digital, Inc.). During each test, both the inner tube (OD: 1.2mm, ID: 0.6mm, curvature: 0.047mm⁻¹) and outer tube (OD: 2.1mm, ID: 1.5mm) were translated and rotated at random order. A total of 38 needle tip position measurements (20 translations at ±15 mm increments and 18 rotations at ±60 degree increments in random order) were taken and compared against the kinematic model [5]. Accuracy in all the tests is quantified by the difference between the final position and desired position of needle tip. The robot had a tip accuracy of 0.31 ± 1.73 mm (Figure 4).

Figure 4: ICH robot tip accuracy performance.

4 Interpretation

This paper presents the preliminary study of a novel MR-compatible steerable needle robot for ICH removal. Experimental results show that the robot was able to operate safely inside a 3T MRI scanner. The needle tip positioning tests showed that the robot’s kinematic model is accurate, although future tests in the MRI scanner using MRI image feedback will be needed to evaluate overall system accuracy with images in the loop. In summary, MRI-guided ICH removal offers both benefits and drawbacks with respect to a CT-guided approach. Fully exploring these will be facilitated by the purpose-built MRI-compatible robot described for the first time in this paper.

Reference