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An MRI Compatible MR-Guided High-Intensity Focused Ultrasound Neonatal Neurosurgery Platform for Intraventricular Hemorrhage

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An MRI Compatible MR-Guided High-Intensity Focused Ultrasound Neonatal Neurosurgery Platform for Intraventricular Hemorrhage

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INTRODUCTION

Intraventricular Hemorrhage (IVH) is a serious neurovascular complication in neonates that can lead to blood clots forming in the ventricular system [1]. Magnetic resonance-guided high-intensity focused ultrasound (MRgHIFU) has been investigated as a non-invasive treatment for clot lysis [2][3]. However, current MRgHIFU systems are not suitable for treating IVH in neonates.

We have developed an MRgHIFU platform optimized for the neonatal brain, which facilitates ergonomic patient positioning and directs treatment through their anterior fontanelle. This platform is based on an MRI-compatible robot designed by our group [4]. This paper describes the optimization of the MRgHIFU platform and its initial validation for treating IVH.

MATERIALS AND METHODS

Treatment is delivered using a 256-element phased-array concave HIFU transducer sourced from a Sonalleve V1 table (Profound Medical, Toronto, CA). The MRgHIFU platform has five degrees of freedom to move the transducer (Fig.1). The platform's electronics and control system are interfaced with a Sonalleve V1 matching circuit, controller board and generator cabinet. Treatment is guided using an Achieva 3.0T TX MRI (Philips Healthcare, Best, NL). We developed an open-source software to interface with the MRI, move the platform, and control HIFU treatment [5].

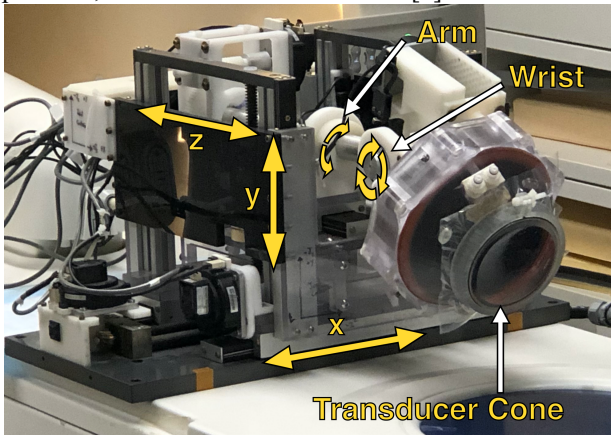

Fig.1: The MRgHIFU platform's five degrees of freedom and coordinate convention.

To optimize the platform to treat IVH, the HIFU transducer was encased in a 3D printed reservoir (transducer cone), which was filled with degassed deionized water. This maintained acoustic coupling during treatment and made it possible to position the transducer above a neonatal patient's head inside an MR-compatible incubator.

Integrating the transducer cone affected the platform's targeting, which required updating and optimizing the MR-compatible robot's hardware and electronics. Some major changes included redesigning the worm drive assemblies, changing the location of limit switches, and redefining the maximum operating range within the MR-bore. Additionally, vitamin E fiducial markers were embedded into the transducer cone's exterior and used to co-register the robot and MR coordinate spaces (Fig.2A). This also allowed overlaying the HIFU focal point and beam path onto MR scans during treatment (Fig.2B).

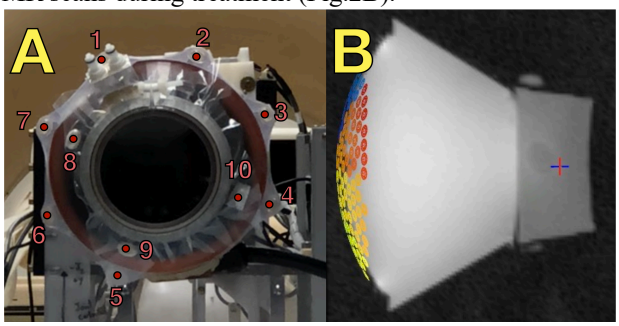

Fig.2: (A) Ten vitamin E fiducial markers (red dots) are embedded onto the transducer cone's exterior. (B) HIFU transducer (coloured circles) and focal point (crosshair) overlayed onto a pre-treatment MRI scan of a phantom.

We first optimized the MRgHIFU platform's targeting ability through simulated brain matter. Subsequently, we validated the platform's ability to lyse blood clots embedded into a brain-mimicking phantom.

Brain-mimicking phantoms were developed to test the platform in a controlled setting. These phantoms emulated the acoustic properties of brain matter, allowed localization of HIFU lesions (both visually and in MR scans), and had interior cavities to imitate the cerebral ventricles.

The platform's targeting accuracy was quantified according to performance criteria outlined in ISO Standard 9283:1998 [6]. HIFU treatment was

delivered to specific coordinates in the phantom and the geometric distance between the intended and actual target locations was measured using T2-weighted MRI scans. An ablation procedure (100W for 30s) was used to create a thermal lesion in the phantom and demarcate the HIFU focal point's location.

The clot lysis efficacy was validated by clotting whole porcine blood inside cavities cast within the phantoms according to an *in vivo* IVH piglet model developed by our group [3]. A boiling histotripsy procedure (500W, 10ms pulse duration, 1.0% duty cycle, and 40s duration) was used to induce acoustic cavitation at the HIFU focal point and cause lysis. After treatment, the remaining solid blood clot mass was used to quantify clot lysis efficacy and the phantom's cavities were inspected for any collateral damage.

RESULTS

The platform could successfully manipulate the transducer cone inside the MR bore and maintain coupling with the phantoms in all the experiments. HIFU treatment was successful and monitored using our open-source software. A total of 127 points were included in the targeting assessment and the platform demonstrated an accuracy of 0.6mm and a precision of 1.2mm (Fig.3). A total of 9 phantoms were included for the quantification of clot lysis efficacy. The platform lysed an average of 97.0%±2.57% of the initial clot mass. The progression of clot lysis was monitored by T2-weighted MR scans (Fig.4). No apparent collateral damage was observed after treatment.

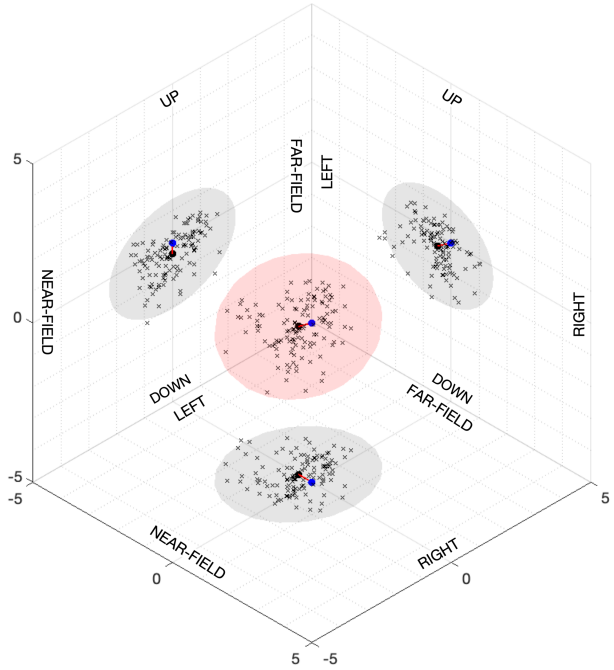

Fig.3: Targeting assessment data plotted on a 3D scatter plot. The targeting accuracy is represented as the distance between the intended (blue circle) and actual (black circle) target locations. The targeting precision is represented by the elliptical 99.7% confidence interval (red ellipsoid).

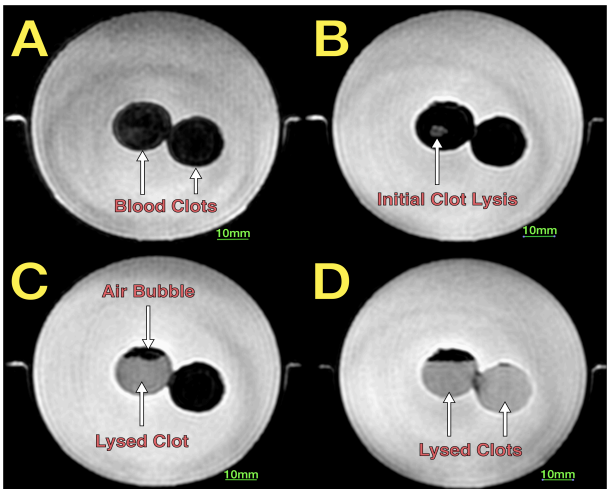

Fig.4: The progression of clot lysis in T2-weighted MR Scans. The phantom and embedded clot can be seen (A) before treatment, (B) after a single sonication point, (C) after half of the clot was treated, and (D) after both halves were treated.

DISCUSSION

The results demonstrate the MRgHIFU platform's high targeting ability and validated its clot lysis efficacy when targeting through simulated brain matter. The developments made after the integration of the transducer cone rectified the targeting ability. Moreover, the platform's accuracy and precision suggest its suitability for the small ventricles in a neonatal brain. Additionally, the platform's ability to lyse a substantial amount of clot mass can provide a greater degree of freedom to optimize treatment for specific patient cases.

These results serve as a successful initial verification of our MRgHIFU platform's potential as a non-invasive treatment of the blood clots in the ventricles of neonates suffering from IVH. Future work will focus on assessing the platform's efficacy at lysing blood clots in an *in vivo* survival study.

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