Mechanical Focal Spot Scanning with a Robotic Assistance System for MRgFUS Therapy

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Introduction

Focused ultrasound surgery (FUS) is a completely non-invasive technique to ablate pathogenic tissue targets. FUS treatment highly benefits from therapy guidance by MRI with its ability for continuous non-invasive temperature monitoring [1]. However, the implementation of a FUS therapy system into an MR scanner is still challenging and demands a combination of complex technologies.

Typically, the spatial dimensions of the US focus are much smaller than the target volume, so that the focus has to be scanned over the target. Scanning of the US focus can be achieved electronically with phased-array transducers or mechanically by repositioning of the US source. Recently, we proposed the combination of fixed focus US transducer and a robotic assistance system for MRgFUS [2]. The combined system potentially overcomes some of limitations of existing MRgFUS system which are often embedded in the patient table. Hence, the spatial flexibility for application of the US wave is limited. In this study, we tested the system for its precision during focal spot scanning procedures in phantom and *in vivo* experiments.

Materials and Methods

The MR-compatible robotic assistance system Innomotion™ (InnoMedic GmbH, Herxheim, Germany) was designed for MR-guided interventions with needles. It offers five pneumatically driven degrees of freedom, and thus can reach over a wide range (≥ 500 mm, i.e. the full FOV of the scanner) within the magnet bore. The robotic system was combined with a fixed-focus US transducer (ν = 1.7 MHz; *f* = 68 mm, NA: 0.44, Siemens) [2]. To optimize handling of the combined setup, the transducer was integrated into a closed treatment unit. A schematic of the closed FUS unit is shown in Fig. 1a. A customized surface coil was integrated into the treatment unit for optimal MR signal reception.

In a first trial of phantom experiments (polyacrylamide (PAA)-egg white, [3]), MR-guided (1.5 T, Siemens Symphony, Erlangen, Germany) focus scanning procedures were performed to assess the relative positioning accuracy of the combined setup. Pre-planned geometric patterns of coagulative lesions were created in the gel phantom. At each target point the US wave was applied for 40 s at an acoustic power of 50 W. Temperature mapping was based on the shift of the proton resonance frequency [4] method using a segemented EPI pulse sequence (3 parallel slices, TR/TE = 91/15 ms, th: 3.0 mm, FOV = 250×250 mm^2, matrix: 192×192, EPI factor: 9, TA ≈ 2.2 s). After sonication, lesion patterns were analyzed semi-automatically on high-resolution, T_2-weighted MR images (TSE, 20 slices, TR/TE = 5460/97 ms, th: 2.0 mm, FOV = 260×260 mm^2, matrix: 512×512). To determine the positions of the individual lesion centroids, the negated signal intensity was analyzed with a center-of-mass calculation. Measured lesion centroids were then compared against the planned target points.

The system was evaluated in an animal experiment with a 3-month-old domestic pig (general anesthesia, mechanically ventilated). An artificial target region was defined in muscle tissue of the animal's right hind leg. First, an L-shaped lesion pattern was created using 9 individual sonications (Δt_{US} = 20 s, P_{US} =30 W) at distances of 5 mm. Second, a confluent lesion was induced by application of 9 sonications (same sonication protocol) along a 3×3 pattern (distances: 2 mm). Thermometry was performed using the segmented EPI sequence with fat suppression (TR = 181 ms). The post-FUS lesions were analyzed on contrast-enhanced (CE) T_1-weighted images (8 ml i.v. injection of Gd-DTPA).

Results and Discussion

A *relative* positioning accuracy of better than 1 mm was found in the phantom trials. Figure 1 shows two of the created lesion patterns – 5×5 (b) and radial (c). Robotically assisted repositioning of the focus could be realized within a few seconds (≈ 5 s/5 mm). For the system's original application with needles, the manufacturer quotes a targeting precision of 1 mm. Therefore, we estimated a *total* targeting precision of about 2 mm which is comparable to that of existing MRgFUS systems [5].

Findings from MR thermometry *in vivo* (ΔT_{max} = 30 K after 20 s of sonication) could be confirmed by post-FUS imaging. In Fig. 1e, a coronal CE T_1-weighted image is given indicating an L-shaped lesion pattern and a confluent lesion. For all sonications, reliable MR imaging and thermometry could be performed without compromises due to operation of the combined robotic FUS setup.

In comparison to existing MRgFUS systems, the combined robotic FUS approach offers a high geometric flexibility. However, electronic beam steering techniques allow for much faster focal motion enabling novel optimized treatment strategies such as volumetric ablation [6]. Nevertheless, the combined setup might help to realize new ways of patient access in MRgFUS therapy. Its full potential might be exploited when combining robotically assisted US source positioning and phased-array technologies for highly flexible, fast focus scanning strategies.

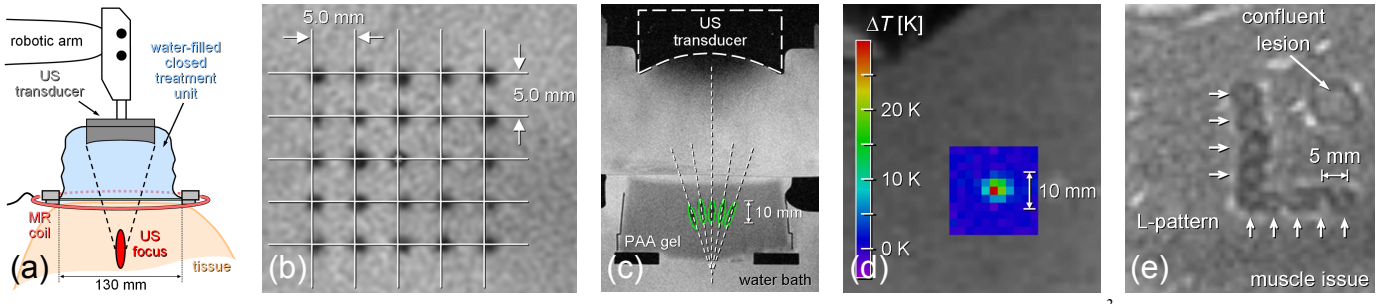

Fig 1: (a) Schematic of the treatment unit. (b, c) Enlarged post-FUS T_2-weighted MR images of 5×5 (5.0×5.0 mm^2 grid indicates positions of pre-planned target points) and radial pattern in PAA phantom. (d) Enlarged image of a single temperature focus in vivo with US beam orientated perpendicular to the imaging plane. (e) CE T_1-weighted post-FUS image delineating an L-shaped pattern of single lesions and a well-defined confluent lesion.

References

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