MR-guided HIFU Thermotherapy with a Robotic Assistance System

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Introduction

High intensity focused ultrasound (HIFU) is a promising, completely non-invasive therapy modality for various diseases such as liver malignancies, prostate and renal carcinomas, or breast cancer [1]. Combing HIFU treatment and MR thermometry (MR-guided focus ultrasound - MRgFUS) enables direct visualization and control of local target heating [2]. Typically, the focus size of the HIFU applicator is much smaller then the pre-planned target volume. Thus, multiple sonications and repositioning of the applicator are required. Repositioning of the ultrasound (US) focus can be achieved either electronically with phased-array transducers or mechanically using different types of actuators. To date, commercial and experimental MRgFUS systems are usually embedded in the patient table of the MR system and the focal spot of the transducers can only access a very limited range. In this study, we combined a fix focus HIFU transducer with a commercially available, fully MR-compatible robotic assistance system originally designed for percutaneous needle interventions. This combination is evaluated for its suitability for MRgFUS applications.

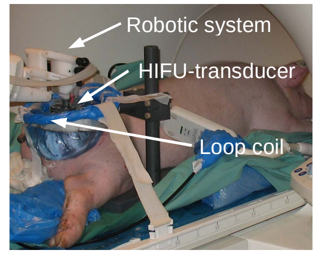

Fig. 1: Robotic assistance system with HIFU transducer. A loop coil is used for MR signal reception.

Materials and Methods

All experiments were carried out on a clinical 1.5 T whole body MR system (Magnetom Symphony, Siemens, Erlangen, Germany). The commercial available robotic assistance system INNOMOTION™ (INNOMEDIC, Herxheim, Germany) was used for positioning and orientation of the HIFU transducer. The arm of the robotic system is mounted on an arc which is attached to the patient table. The assistance system can be moved in 6 degrees of freedom. Originally designed for MR-guided needle interventions, the system features a distal instrument holder with passive MR markers for localization. The connection of the US transducer with the assistance system is achieved via a dedicated holder that uses the same mechanism as the existing needle holder. A fix-focus transducer (ν = 1.7 MHz, focal length: 68 mm, NA = 0.44; elliptical 6 dB-focus: Ø = 1.1 mm, length = 8.1 mm; prototype, Siemens Medical Solutions) was mounted to the head of the robotic system (Fig. 1), so that the sonication axis coincided with the needle axis and the existing intervention planning software of the system could be used. The transducer was connected to a power amplifier located outside the RF cabin using a specially designed transmission line with integrated filters to suppress unwanted coupling with the MR signal.

First, the positioning accuracy of the setup was assessed with a transparent polyacrylamide (PAA) gel phantom. The PAA phantom was enriched with egg white as temperature sensitive indicator and guaranteed well-defined acoustic parameters [3]. Initially, planning images were acquired, a target was defined with the assistance system's planning software and the HIFU transducer was positioned and oriented by the robot. To achieve optimal coupling of the US waves into the phantoms, both transducer and phantom were embedded in a degassed water bath. Proton resonance frequency (PRF) temperature maps (FLASH, TR = 20 ms, TE = 15 ms, SL = 5 mm, FOV = 256×256 mm^2, matrix: 256×256) were acquired in a slice parallel to the sonication axis. An in-house developed software tool (IDL 6.3, ITT Visual Information Solutions, Boulder, CO, US) allowed online-calculation and illustration of temperature difference maps on an external PC which was connected to the host computer of the MR scanner via a TCP/IP connection. A sonication period of 1 min was used to create nine single lesions at distance of 5.0 mm along two perpendicular axes in the PAA-phantom. Five individual sonications with a distance of only 1 mm were used to induce a confluent lesion. The relative positions of the HIFU-induced lesions were evaluated by calipers and on T_2-weighted MR images (SE, TR = 4000 ms, TE = 143 ms, SL = 3 mm, FOV = 250×250 mm^2, matrix: 384×384).

The performance of the combined robotic assisted HIFU treatment system was investigated in an in vivo experiment with a fully anesthetized, 3 month old domestic pig. A degassed water-filled bag was fastened to a ring holder system, so that the HIFU transducer was fully immersed in water to assure optimal coupling of the US wave into the porcine tissue. This setup was used to perform sonications of the pig's right hind leg muscle tissue under MR guidance. Local temperature maps were obtained (FLASH, TR = 20 ms, TE = 15 ms, SL = 5 mm, FOV = 300×300 mm^2, matrix: 256×256) and monitored equivalently as described for the PAA-phantom experiment.

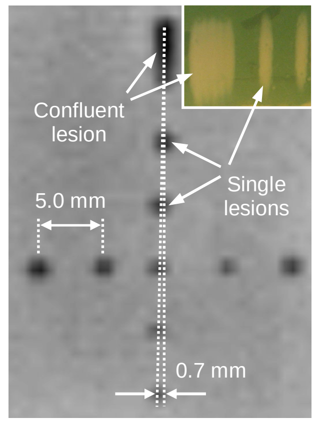

Fig. 2: Photograph (insert) and enlarged MR image of the lesions in the PAA-phantom. Five individual sonications at a distance of 1.0 mm were used to create a confluent lesion.

Results and Discussion

A MR-image (coronal slice orientation) of several thermally-induced lesions at pre-defined positions in the PAA-phantom is shown in Fig. 2 to asses the accuracy of the robotic assisted US focus positioning. The robotic assistance system was able to move the HIFU transducer from one position to the next within less than 10 s. Both caliper and MR image based measurements showed a maximal spatial deviation of 0.7 mm at a positioning distance of 30.0 mm. A confluent lesion could be successfully created (Fig. 2) by using 1 mm repositioning steps between five individual sonications. A temperature difference map at the end of one sonication period is shown in Fig. 3(a) overlaid onto a corresponding magnitude image. A well defined US focus is visible and a maximal temperature increase of 17.5 K was measured.

A temperature difference map at the end of one in vivo sonication is shown in Fig 3(b). The US focus is clearly visualized, and, after the sonication period of 1 min, a temperature increase of 24.5 K was measured. However, this image also reveals a major problem of PRF-based MR thermometry, as no temperature change could be measured in the pig's subcutaneous fat tissue.

In this study, a HIFU transducer was combined with a commercial available robotic assistance system for MR-guided needle interventions. The experiments demonstrated the feasibility of accurate and fast robotic positioning of the US applicator. The system proved to be fully MR-compatible; neither the positioning of the transducer nor the HIFU treatment influenced the MR image quality. Several technical improvements regarding the coupling of the US into tissue or MR thermometry methods still need to be implemented. Nevertheless, these initial experiments already show the potential of the combined robotic assisted HIFU system which provides an anterior access to the patient in combination with fast and precise re-positioning.

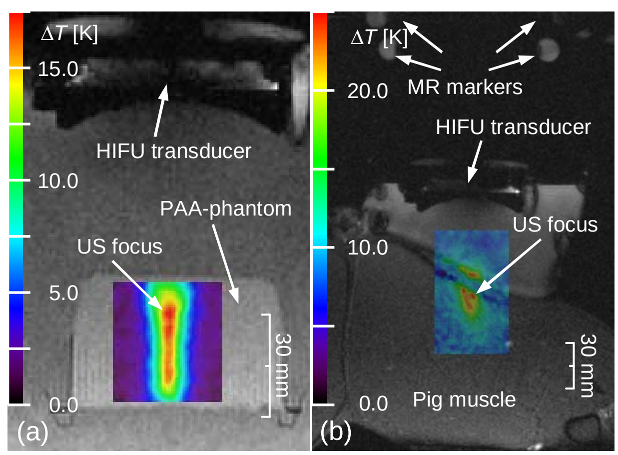

Fig. 3: Magnitude images of phantom (a) and in vivo (b) experiment with overlaid temperature maps acquired at the end of the sonication period (1 min).

References

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