HYBRID MR/US-GUIDED HIFU FOR ABDOMINAL TARGETS: IN VIVO DEMONSTRATION OF 3D MOTION CORRECTION AND FOCAL POINT LOCKING ON AN ABSOLUTE REFERENCE MARKER

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Target audience: Scientists/Radiologists performing magnetic resonance guided interventions using HIFU.

Purpose: HIFU treatment of moving targets in the abdominal region is ideally performed with continuous motion tracking in order to readjust the focal point position such that it locks onto the target. Hybrid 2D US and MR imaging has been proposed for prospective motion-tracking of mobile organs promising better control of the HIFU therapy [1]. While the motion compensation enabled the in-plane isotropy of the lesion (that is, the spatial precision), none of the previous studies [1,2,3] used an absolute target (e.g. a real- or pseudo-tumor) to demonstrate the spatial accuracy of the treatment. In order to achieve this, we created user-defined ballistic targets [4], as absolute reference markers for hybrid US-MRgHIFU in vivo.

Methods : A hybrid US-MR guided HIFU method with 3D motion compensation and slice tracking of MR thermometry that dynamically achieves focal point locking-on to a pre-defined absolute target was used in vivo. The marker was not observable in ultrasound images, was irreversible, MR-compatible, MR-detectable, and a well-established histology staining technique. Three pigs were included in the study (GA, ventilator driven breathing). The marker was created in the liver (N=2) or in the renal cortex (N=1). Experiments were conducted on a 3T clinical scanner. Prior to ablation the marker was visualized using an inversion recovery (IR) prepared T1-w respiratory gated 3D sequence with near isotropic resolution (TIR/TE=650/2.8ms, voxel size 1.5x1.5x2.4 mm^3, matrix 256 x 256 x 84, segments=43, GRAPPA = 2, PF = 0.75, TA=5 to 7 min depending on breathing rate, acquisition window=400ms) and its coordinates were registered in the HIFU reference frame. The gating signal was generated by a software interface that analyzed in real time the ultrasound images obtained inside the magnet bore and tracked the hyper-echogenic features (optical flow). A train of 90 echoes was acquired during each quiet phase of exhalation, until the 3D data set was completed. During HIFU ablation, a MR-based pencil beam navigator was used to compensate the antero-posterior motion, while an US imaging system provided 2D organ motion information in the main plane of motion (coronal), using the subxiphoid acoustic window at 25 fps. US and navigator information was combined into complete 3D target tracking and fed to the HIFU device for electronic steering (60s, 200 W ac) and to the MR acquisition CPU to realign in real time the k-space segments of a multi-slice segmented GRE-EPI PRFS sensitive sequence (TR/TE=53/5.2 ms, TA=0.6s/slice, 121 water selective excitation, 1.6x1.6x5 mm^3 voxel, EPI factor=11, coronal and sagittal sequential slice acquisition). Reference-less and multi-baseline thermometry was available. The animal was sacrificed 7 days post- operation and standard histology was performed.

Fig. 1. *Experimental setup: 1. shielded US imaging transducer, 2. interventional MR coil, 3. HIFU device, 4. Rib shielding, 5. animal's holder. The pig was positioned in the right lateral decubitus position, US imaging was acquired subxiphoidally.*

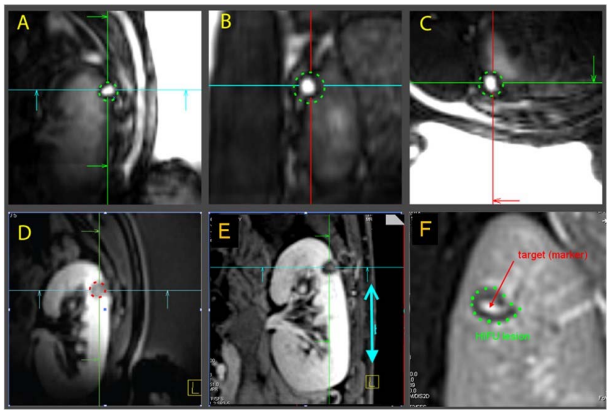

Fig.2. *Visualization of the histological marker in situ prior to the HIFU therapy in the pig kidney (A-C), the NPV immediately after treatment (E) as well as at 7D post-ablation (E – sag, F – coronal, zoom x 2). Note the high IR contrast of the marker and the accurate matching to the HIFU lesion location.*

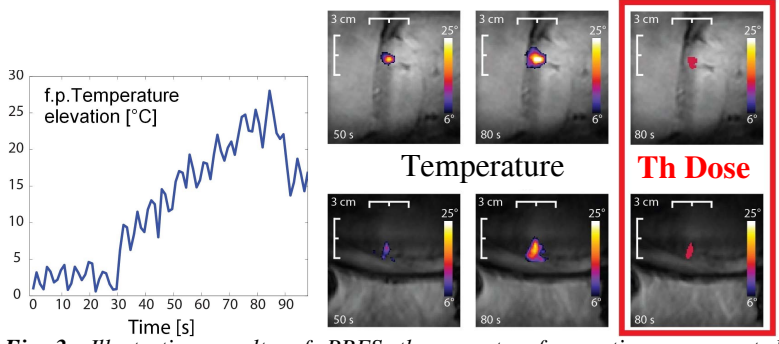

Fig 3. *Illustrative results of PRFS thermometry for motion-compensated sonication at the target marker. Left: focal point temperature elevation versus time. Right: temperature maps (at 50s and 80s sonication,) and cumulated thermal dose, coronal (up) and sagittal (down) acquisition planes.*

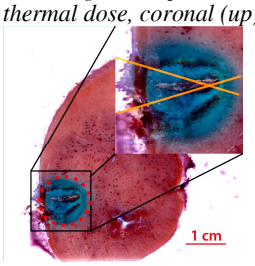

Fig.4. *Gross pathology after 3 weeks post-mortem formalin fixation. The decolored area produced by the HIFU ablation and the blue methylene staining are accurately matched. The upper-right inset illustrates the incident HIFU beam cone. The small central tissue deletion zone that was produced by RF ablation is several times smaller than the HIFU-induced lesion. A haemorragic rim is typically obtained in the kidney surrounding the lesion.*

Results: The temperature maps showed reduced intra-scan ghosting artifacts, a high SNR and low geometric distortion. Motion-compensated US-MRgHIFU ablation matched with sub-millimeter accuracy the moving target, see Fig.4. Optical flow tracking of US images in vivo in the liver and in the kidney using the subxiphoidian acoustic access was stable and reliable. This was also the case for tracking the motion out of US imaging plane using the MR navigator echo.

Discussion and Conclusion. Adjustments of the US imaging probe position was required in order to have the principal component of motion positioned as much as possible in the US imaging plane. The temporal resolution of the motion correction was set by the TR parameter of the GRE-EPI sequence (53 ms). Motion through the US imaging plane may reduce the stability of the optical flow tracking algorithm. Only single focus ablation was performed in this study. Future studies will address volumetric sonication and the automatic feedback control of the temperature evolution coupled to 3D motion compensation in vivo. The hybrid US-MR guided HIFU planning and treatment method was successfully demonstrated to achieve sub-millimeter accuracy in moving organs in vivo.

References. [1] Auboiroux *et al.* Phys Med Biol 57:159-171 (2012); [2] Ries *et al.* MRM 64:1704-1712 (2010); [3] Holbrook AB et al, MRM, 2013 Mar 4, [4] Petrusca L *et al*, J Transl Med. 2014 Jan 16