HYBRID US-MR GUIDED HIFU TREATMENT METHOD WITH 3D MOTION COMPENSATION

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

Purpose: MRgHIFU treatment of moving targets in abdominal region is ideally performed with continuous motion tracking in order to readjust the focal point position to lock on target. Previous approaches applied fast MR thermometry imaging with advanced real-time processing of MR images to achieve controlled thermal treatment [1,2]. In [3], MR navigator echo was used to track organ motion and guide HIFU, while the same tracking information was used for slice tracking of MR thermometry. Combining US imaging and MRI into a hybrid system to guide HIFU treatment is a novel approach that could be useful in the treatment of mobile organs. The safety of US and MRI has been clinically proven and both feature complementary advantages promising better control of the therapy. Recently, US-based 2D motion-compensated HIFU sonication was reported in [4]. The out-of-plane motion was not addressed in that approach. Since the target tracking is performed by US there might be no need for MR-based tracking. However, 3D real time MR-compatible US imaging is not yet available, therefore MR-based navigator may be complementary used to track the out-of-plane motion. Intra- and inter-scan MR motion artifacts pose a challenging problem when measuring temperature inside the abdominal region [5]. Here, it is demonstrated in a phantom study the feasibility of a novel hybrid US-MR guided HIFU with 3D motion compensation and slice tracking of MR thermometry. MR-based navigator was used to compensate the out-of-plane motion, while US imaging system provided 2D organ motion information in the main plane of motion, which were combined into complete 3D target tracking and fed to HIFU device for electronic steering and to MR acquisition CPU to realign in real time the k-space segments. To our best knowledge, this is the first truly hybrid US-MR guided HIFU method which achieves full 3D prospective motion compensation.

Methods: A segmented GRE EPI sequence was modified to acquire MR navigator echo [6], pencil-beam navigator with 2D RF excitation, before the acquisition of each segment of k-space. MR navigator was oriented perpendicular to the US imaging plane. The following acquisition parameters were used for MR thermometry: TE/TR = 10.3/30 ms, EPI factor = 13, voxel size = 1.56 × 1.56 × 5 mm, image matrix = 128 × 116, FOV = 200 × 180 mm^2, BW = 797 Hz/px, flip angle = 10º, TA = 600ms/slice, two interleaved orthogonal slices . Temperature maps were calculated using the open border near-harmonic 2D reference-less method [7]. The open border was adjusted to avoid the beam propagation cone in the sagittal plane and the navigator-induced signal saturation region in the coronal plane. The experiments were performed on a 3T clinical MR system. The HIFU transducer consisted of 256 phased-array elements with operating frequency of 974-1049 kHz, natural focal length and aperture 130 mm and 140 mm, respectively. Dedicated, in-house developed software was used for treatment planning and control. The MR –compatible 2D US clinical system was used with a phased-array transducer (256 elements, bandwidth 1.8 – 4 MHz) operated inside the MR bore. The optical flow algorithm was used on the US images to extract organ motion within the US imaging plane (2D). This information was fed in real-time to the HIFU device and MR scanner. The out-of-plane motion was tracked by MR pencil-beam navigator and that information was also fed to the HIFU device and MR scanner. Slice tracking of MR thermometry (on a segment-per-segment basis) as well as the focal point position correction were thus performed in 3D. The ex vivo degassed liver sample was driven by a mechanical ventilator to produce the periodic and non-rigid breathing-like motion pattern.

Results: The simultaneous MR-US imaging was achieved without mutual interferences. MR thermometry imaging benefited from the applied 3D slice tracking as the organ motion was prospectively "frozen", while segmented EPI acquisition provided higher SNR and less geometrical distortions compared to the single-shot approach used most commonly in MRgHIFU interventions. Figure 1 shows one example of temperature maps in coronal and sagittal orientation, as well a sample US image demonstrating motion tracking set-up and calculated tissue displacement The motion amplitude of the ex vivo sample in this example was 12 mm, as plotted herein.

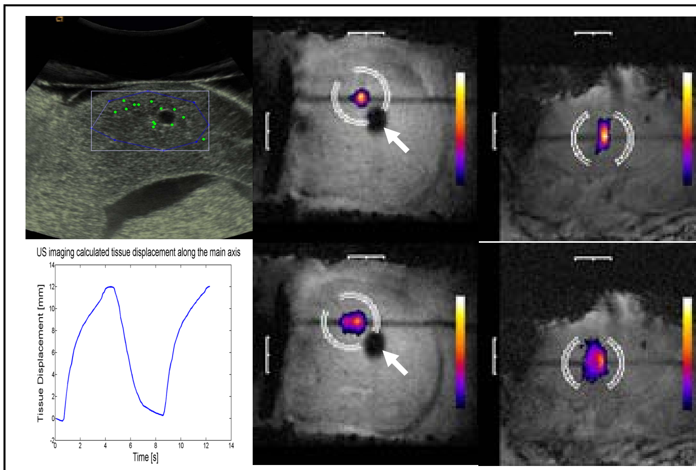

Figure 1 Left: US image with motion tracking features (up), US-based tracking displacement of the tissue (down); Middle: Coronal temperature maps with (up) and without (down) motion correction; Right: Sagittal temperature maps with (up) and without (down) motion correction. All temperature maps are acquired with 3D slice tracking of MR thermometry. Signal void region (pointed by white arrows) is caused by the saturation effect of MR navigator oriented through slice. (Temperature elevation scale: +5 to +50 °C, FOV = 200mm)

Discussion: The motion compensation of the HIFU treatment in free breathing subjects is important, since it enhances the focal temperature elevation and reduces the risk of thermal damage to the surrounding healthy tissue. In our ex vivo experiment, temperature elevations were 1.9 times higher in compensated compared to the uncompensated experiment. We report on the feasibility of a clinical 3 T MRI and clinical 2D US imaging system to be combined into a hybrid guidance of HIFU to achieve 3D motion-compensated treatment and accurate MR thermometry. Active target tracking was achieved with near real temporal resolution. Optical flow tracking of US images was stable and reliable as well as tracking by MR navigator echo. Minor RF interferences were observed in the far field of the US image due to HIFU sonication, but had no effect on the optical flow tracking. The effective duty-cycle of the HIFU sonication was close to 100%. Although the method was tested on periodic motion patterns, it could be applied to aperiodic ones, since its near real-time tracking allows efficient focal point position correction, while reference-less temperature mapping is motion insensitive.

Conclusion: Hybrid US-MR guided HIFU treatment was successfully demonstrated achieving sub-millimeter accuracy. Motion-related MR artifacts were removed by slice tracking, while near real-time focal point position correction with high frequency managed to lock on target compensating organ motion without using a predictive approach. Reference-less PRFS-based MR thermometry required no a-priori knowledge of organ motion pattern

References: [1] de Senneville *et al.* MRM 57:319-330 (2007); [2] Ries *et al.* MRM 64:1704-1712 (2010); [3] Celicanin *et al.* Proc. ISMRM, p. 560 (2012); [4] Auboiroux *et al.* Phys Med Biol 57:159-171 (2012); [5] Rieke *et al.* JMRI 27:376-390 (2010); [6] Hardy *et al.* JCAT 15:868-874 (1991); [7] Salomir *et al.* IEEE TMI 31:287-301 (2012);