Real-Time Method for MR Thermometry and Treatment of Mobile Organs by MRgHIFU

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Introduction: High-intensity focused ultrasound (HIFU) is a promising new technique for noninvasive thermal therapy. Motion is a severe problem that prevents the application of MRgHIFU system to the thermal treatment of organs that are subject to motion during respiration. Temperature monitoring with proton resonance frequency (PRF) shift method of MR thermometry exhibits artifacts when applied to abdominal imaging due to motion. Usually, the temporal resolution of thermometry is increased using acceleration techniques, such as parallel imaging, which leads to a reduction of SNR and subsequently less accurate thermal maps in order to make it motion insensitive. Organ motion can be discriminated as intra- or interscan motion by duration and period when it is present. Intrascan motion is the motion present during the image acquisition and results in ghosting and blurring artifacts. On the other hand, interscan motion is present in the period between the consecutive slice acquisitions, and could have influence on thermal dose and temperature map calculation [1]. Here, we try to combine intra- and interscan motion compensation for stabilization of thermometry imaging, and simultaneous real-time MRgHIFU focal point steering.

Abdominal organs, such as liver and kidney, move predominately along anterior-posterior direction during respiration [2-4]. The pencil-beam navigator [5] could be used for motion compensation of thermometry imaging, and to provide information about target motion to HIFU system for focal point adjustment.

The previous real-time thermometry and treatment techniques were based on application of 2D image registration, which provided in-plane tracking of target. Recently, Ries et al. [6] demonstrated a real-time 3D target tracking method, which was also using a 2D image registration for in-plane target tracking and 1D pencil-beam navigator for the though plane motion compensation. Our approach differs to the previous in the way the pencil-beam navigator is used. The navigator echo is used for both intra- and interscan motion compensation of thermometry imaging and real-time HIFU focal point adjustment.

Methods: Partial EPI acquisition along with pencil-beam navigator was implemented on a 3.0 T whole-body scanner. The navigator is acquired before each k-space segment of thermometry EPI acquisition, and prospective slice correction is performed. Slices are repositioned based on displacement provided by navigator feedback. 1D navigator feedback data is converted into 3D spatial coordinates of scanner reference system to allow tracking of organ motion by arbitrary positioned navigator. This spatial coordinates are sent in real-time to HIFU system to adapt its focal point accordingly. Simultaneously, thermometry slice position is updated according to displacement measured by navigator and this achieves intra- and interscan motion compensation of thermometry imaging. Motion compensation is applied, so imaged objects are static in the images. This allows easier and accurate thermal dose calculation. Partial k-space acquisition with zero-filling was used in the phase-encode direction to allow high spatial resolution while minimizing T2* apodization effects on the image and further increasing the slice efficiency per TR. The main challenge with the calculation of PRFS-based thermometry in presence of motion is the modification of the baseline phase map which induces erroneous temperature measurement. Therefore, a reference-free method based on the estimation of the phase background from an unheated thin border around the focal point was used for the calculation of thermal elevation [7].

The HIFU system consisted of a 256 multi-element transducer driven at 1.031 MHz with an acoustic power of 140 W. Navigator coordinates were processed on-the-fly with on-site modified ThermoGuide software and the electronically steered position of the focal point position was updated every 100 ms according to the navigator data. The time lag between navigator acquisition, and focal point position update was below 100 ms and allowed the lock onto tissue displacement (9 respiratory cycles/minute).

MR-guided HIFU ex vivo experiments were performed on a sample of turkey muscle moving along the H/F direction. The displacement was ensured by a balloon connected to an anesthesia ventilator in order to mimic respiration-induced motion (over maximum amplitude of 7 mm). Single point continuous wave sonications in presence of motion were performed with and without focal point lock onto tissue position. The main acquisition parameters were FOV = 192x192 mm, voxel = 1.5x1.5x5 mm, TE = 8.69 ms, TR = 80 ms, EPI factor = 9. In vivo acquisitions on sheep liver under general anesthesia were also performed without HIFU sonication to evaluate sequence stability.

Results & Discussion: Figure 1 shows two images of ex vivo experiment. The organ motion is corrected by navigator echo feedback, and compensated by real-time slice correction, so that objects are static on the images. Blurring and ghosting artifacts are eliminated due to intrascan motion correction. Both images are acquired with motion compensation, and the difference is that the HIFU focal point steering was used only during acquisition of right image. The lock of the focal point position onto tissue motion allowed restoring the sharp profile of the focal point, without elongation along main axis of tissue displacement. Subsequently, the temperature elevation at the focal point after 16 s of sonication was found to be significantly higher with motion lock (14°C) as compared to the immobile sonication (8°C). By taking into account organ motion and perfusion of organ, this comes out as a valuable result that will shorten the treatment time by avoiding the cooling periods that appear during respiratory gated HIFU treatments. For both in vivo and ex vivo acquisitions, the residual tissue motion was found to be smaller than one pixel and the SNR to be approximately 20.
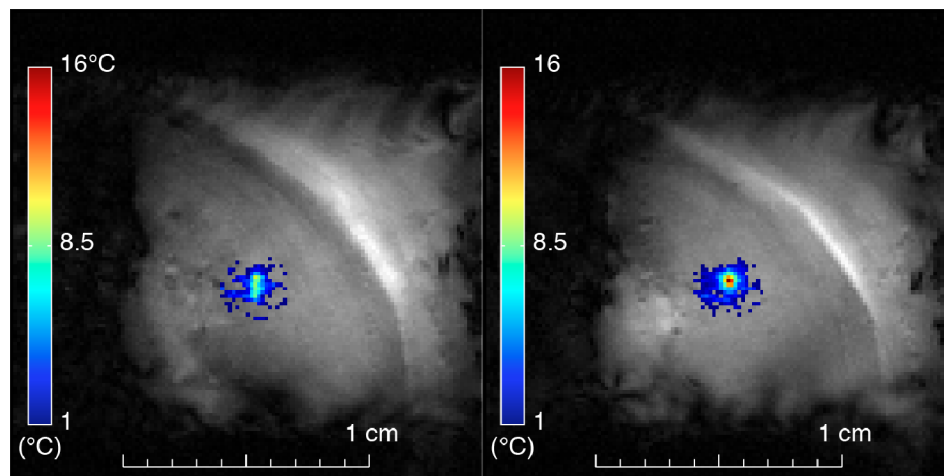

Figure 1 Thermometry image of moving phantom (turkey muscle) in a coronal plane with real-time slice correction without (left) and with (right) real-time HIFU focal point electronic steering

Conclusion: A novel real-time method for MR thermometry motion compensation and simultaneous MRgHIFU treatment has been demonstrated. The motion of organ is compensated by real-time slice correction. Blurring and ghosting artifacts are eliminated due to intrascan motion correction. It allowed accurate MRgHIFU single point sonication, without significant difference when compared to a sonication into an immobile target.

References: [1] Rieke et al. JMRM 27:376-390 (2008); [2] Harauz et al. JNM 20:733-735 (1979); [3] Weiss et al. JNM 13:758-759; [4] Shimizu et al. Rad. Oncol. 50:367-370 (1999); [5] Hardy et al. JCAT 15:868-874 (1991); [6] Ries et al. MRM 00:000-000 (2010); [7] Salomir et al. IEEE TMI, in press (2011)