ARFI-prepared MR-guided transcostal HIFU in sheep liver *in vivo* using a high resolution hybrid ARFI/MRT GRE-EPI sequence

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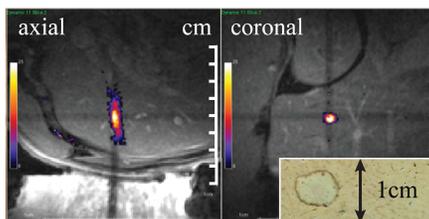
Objectives MR-ARFI (Acoustic Radiation Force Impulse) is a displacement-sensitive sequence where the transient displacement induced by the momentum transfer to the tissue from the HIFU beam is encoded using motion encoding gradients. It is similar to elastography, though elastography is usually based on the periodic displacement induced by low frequency waves. As the local displacement is proportional to the acoustic intensity, MR-ARFI permits the localization of the HIFU focal spot as well as providing information for planning, monitoring and optimization of MRgHIFU (assessment of focusing quality and targeting, mapping of tissue stiffness and immediate evaluation of tissue ablation). HIFU, however, also causes tissue heating, since temperature elevation and tissue displacement produced by the radiation force are always, to a various degree, associated. Repeated ARFI measurements (e.g. during phase law adjustment) may thus induce a significant thermal accumulation and must therefore be monitored. Significant temperature increases may occur near high absorbing structures, like bones or air-filled bowels, whilst the perfused target areas do not present a significant thermal elevation. The objective of this present work was to implement and validate in sheep liver *in vivo* a rapid MR sequence for the simultaneous mapping of ARF-induced tissue displacement and temperature elevation, with temporal resolution of the order of one second, and to use it as preparation for HIFU ablation in situ.

Materials & Methods An RF-spoiled segmented EPI gradient echo sequence was modified to integrate a symmetric bipolar motion encoding gradient (MEG) in the slice-select direction (max amplitude = 38mT/m, slew rate = 100T/m/s, duration = 4.4ms). This MEG was inserted between the RF excitation pulse and the EPI readout. The HIFU burst (5.5ms-long, overlapping the second MEG lobe) was produced by a 256 multi-element transducer (Imasonic, Besançon, France) with an acoustic power ranging from 200W to 260W. The natural focal length and aperture of the transducer are respectively R = 130mm and d = 140mm (f = 1.030 MHz). Coronal images perpendicular to the HIFU beam were acquired on a 3T MR system (TIM Trio, Siemens AG, Germany). The main imaging parameters were: FOV = 128x128mm, voxel = 1x1x5.0mm, TR/TE/FA = 50-300ms/16ms/15ms, Partial Fourier = 6/8, echo spacing = 1.58ms, loop coil (11cm). Interleaved alternating MEG polarity was used and two phase maps, denoted Φ^+ and Φ^- (see Fig.1), were obtained. Temperature (MRT) and ARFI maps were derived from two successive acquisitions by performing respectively the average and difference of the phase maps [2,3,4]. To reduce eddy-current-induced phase shift artefacts, different phase references were used for even and odd measurements (i.e. double reference). Phase unwrapping, temporal subtraction of reference phase background (i.e. without HIFU bursts) and computing of temperature elevation and tissue displacement at each pixel were performed on-the-fly with on-site modified ThermoGuide software (Image Guided Therapy, Pessac-Bordeaux, France).
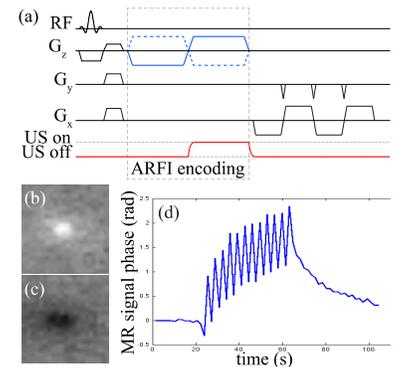

Figure 1: (a) Dual Temperature-ARFI Sequence principle. (b) resulting phase in vitro for positive encoding and (c) for negative encoding. (d) phase evolution at the focal point
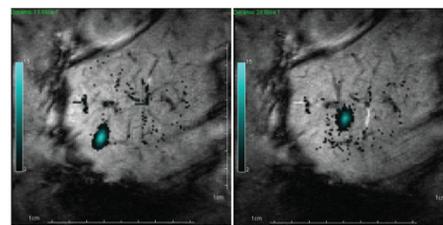
Transcostal MR-guided HIFU *in vivo* liver experiments were performed on ventilated sheep using a respiratory trigger that allowed the successive acquisition of Φ^+ and Φ^- during the same expiration. The capacity of transcostal focusing of the HIFU beam was verified using ARFI measurements at different prescribed locations, thermal ablation was then performed with respiratory-gated CW emission mode at the identified reachable locations. Ablative sonications were monitored with the same basic sequence with MEG removed and TE set to 8.5ms. Semichronic MRI follow-up was performed at day 7 and post-mortem histological analysis was conducted.

Results. The hybrid ARF-sensitive/PRFS temperature-sensitive sequence permitted to visualize in near real-time the tissue displacement in the focal plane and the associated increase in temperature with a temporal resolution of approx. 6s (as set by the mechanical ventilator) and precision of 0.5μm and respectively 0.5°C in liver *in vivo*. An increase in the EPI factor of the sequence decreases by the same factor the heating per image (lower number of HIFU pulses being generated while encoding one k-space) but may increase the level of geometric distortion.

Figure 2: ARFI measurement in sheep liver with electronic steering. Coronal plane

Figure 3: Thermal ablation in sheep liver with CW HIFU sonication and post-portem macroscopic histology (bottom-right incrustation).

In vivo measurements in sheep liver demonstrated the efficiency of the method for the localization of the HIFU focal spot and enabled the localization of focal point positions that could be reached with electronic steering without significant loss due to the rib cage. The sharp focal ablation achieved by MR-ARFI-guided HIFU was proved by the post mortem gold standard histology (see incrusted macroscopic lesion slicing in Fig. 3).

Conclusion High-resolution hybrid ARFI/MR-thermometry was demonstrated *in vivo* in sheep liver. In situ preparatory assessment of focusing quality, prior to ablative CW HIFU sonications, significantly increases the safety and the efficiency of the treatment. Moreover, any thermal risk during ARFI acquisition (including potential heating of the ribs) can be avoided due to the dual monitoring capability of the sequence

References [1] Souchon *et al.* MRM 2008. [2] Plewes *et al.* JMRI 1995. [3] Le *et al.* MRM 2006. [4] McDannold *et al.* MedPhys 2008