

MAGNETIC RESONANCE ACOUSTIC RADIATION FORCE IMAGING (MR-ARFI) FOR THE ESTIMATION OF LOCAL VISCOELASTICITY AND ANISOTROPY

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Purpose: In this study, we propose to use MR-Acoustic Radiation Force Imaging (MR-ARFI) as a transient elastography method to estimate the viscoelasticity and the anisotropy of an ultrasound absorbing medium.

Methods: MR-ARFI¹ uses the acoustic radiation force induced by a focused ultrasound beam to generate a remote micrometric displacement (push) at the ultrasonic focal region. This push results in the propagation of a transient shear wave of velocity c_s that is encoded in the MRI phase signal by a motion-sensitized sequence synchronized to the push. The resulting MR-ARFI phase profile depicts the ARFI spot, whose size increases with tissue stiffness. A previous quantitative MR-ARFI method² has been proposed that allows estimating the local shear modulus μ of the medium around the focal spot, through the identification of the MR-ARFI profile. However, that work was limited to isotropic media, and the viscoelastic relaxation time τ was fixed arbitrarily. In this work, we propose to estimate τ following the approach published by Kaye et al.³ and Dadakova et al.⁴, which consists in fitting the phase signal at the focal spot for different temporal synchronization steps. Process is also extended to tissue anisotropy estimation, by performing individual fits on each radial profile extracted from the MR-ARFI phase image (Fig. A). The method is first validated on a homogeneous phantom calibrated for elastography (CIRS, USA; datasheet $\mu_{ref} = 5.9 \text{ kPa} \pm 5\%$). Second, changes in biomechanical properties are estimated before and after a HIFU thermal ablation in ex vivo calf muscle tissue.

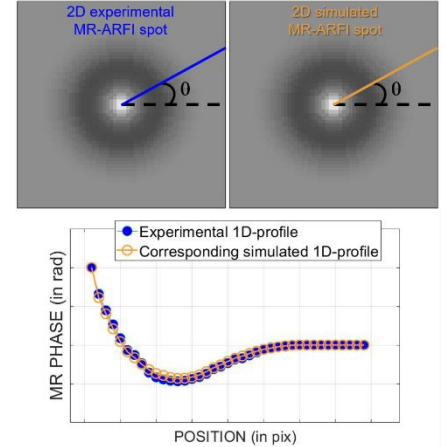


Figure A – Fitting method to estimate direction-dependent shear modulus $\mu(\theta)$

Results: In the CIRS phantom, the value determined for τ is 3.3 ms at the focal spot. Using our MR-ARFI model, the polar representation of μ is isotropic, with an average value of $7.9 \text{ kPa} \pm 3\%$ (Fig. B). In the calf tissue, τ decreases from 7.5 ms pre-HIFU to 4.5 ms post-HIFU, while μ globally decreases (Fig. C) suggesting that the meat softens as a result of heating. Figure C shows the shear modulus angular distribution both pre- and post-heating in calf tissues that appear to be highly anisotropic. The acquisition time for polar map of μ was 4 s, corresponding to the acquisition of 2 MR images with opposite motion sensitivity polarities.

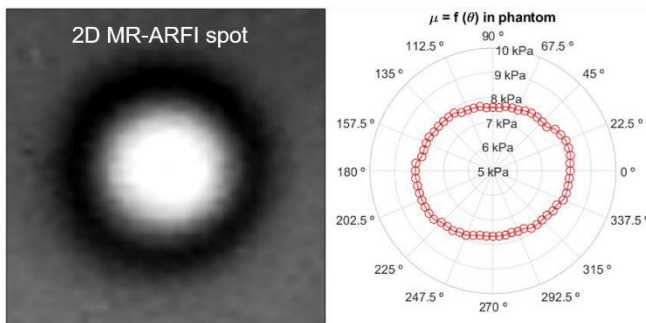


Figure B – MR-ARFI phase profile (left) and resulting μ polar plot (right) in the CIRS phantom

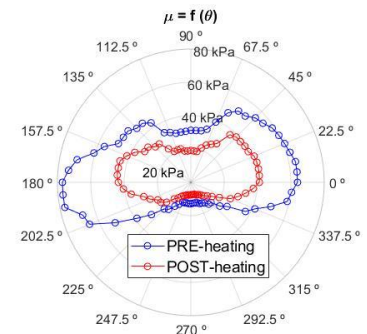


Figure C – Resulting μ polar plot pre- (blue) and post-HIFU (red) in calf tissues

Discussion: Quantitative MR-ARFI with viscoelastic model and anisotropic analysis provides shear modulus in the same range as μ_{ref} in the CIRS phantom. After the HIFU experiment, cutting the calf tissue revealed a very irregular fiber orientation, consistent with the anisotropy observed with MR-ARFI. The maximum temperature rise reached in this experiment was $50 \text{ }^\circ\text{C}$, which results in meat tenderization, as already reported in the literature⁵.

Conclusion: The proposed method allows for local, quantitative, and direction-dependent viscoelasticity measurements around the focal spot. Its ability to provide polar maps of μ makes it a promising method to gain insights into biological tissue mechanical properties. The modification of τ found with HIFU heating calls for a further refined modeling of viscoelasticity to extend the method to the monitoring of HIFU ablations.

References: [1] McDannold et al, Med Phys, 35-8, 2008 [2] Vappou et al, Phys Med Biol, 63-9, 2018 [3] Kaye et al, Magn Reson Med, 69-3, 2018 [4] Dadakova et al, Magn Reson Med, 79-2, 2018 [5] Wu et al, Magn Reson Med, 45-1, 2001