

# Combined MRE and SPAMM tagged MRI for the analysis of large strain soft tissue mechanical properties

K. M. Moerman<sup>1,2</sup>, A. M. Sprengers<sup>2</sup>, C. K. Simms<sup>1</sup>, A. E. Bohte<sup>2</sup>, R. M. Lamerichs<sup>3</sup>, R. Sinkus<sup>4</sup>, and A. J. Nederveen<sup>2</sup>

<sup>1</sup>Trinity Centre for Bioengineering, University of Dublin, Trinity College, Dublin, Ireland, <sup>2</sup>Radiology Department, Academic Medical Centre, Amsterdam, Netherlands, <sup>3</sup>Philips Research, Eindhoven, Netherlands, <sup>4</sup>Radiology Department, CRB3, Hôpital Beaujon (U773), INSERM, Clichy, France

**Introduction:** Clinical conditions affecting soft tissue often present with altered mechanical properties (e.g. tumours, fibrosis and/or malignancy). Hence, the MRI based non-invasive analysis of soft tissue mechanical properties has been the focus of many fields of research. Soft tissue mechanical properties are non-linear with respect to strain, strain-rate and frequency and, due to strain stiffening of soft tissue, elasticity differences (e.g. between malignant and healthy tissue) may become more pronounced at higher strains. Analysis of non-linearity with respect to strain provides added tissue contrast capabilities and is therefore of interest to the current study. However this requires measurement of mechanical properties across a range of strain levels. Unlike ultrasound based methods which heavily rely on experimental boundary conditions, the current study aims at developing methods independent of these. Mechanical property measurement at macroscopic strain levels, such as those based on SPATial Modulation of the Magnetization (SPAMM) tagged MRI [1], require complex inverse (e.g. finite element) analysis and detailed knowledge of the boundary (e.g. loading) conditions. MR Elastography (MRE) uses imaging of the propagation of low-frequency acoustic waves within soft tissue and allows for the estimation of shear elasticity and viscosity properties independent of boundary conditions, and has been shown to be beneficial in the study of liver fibrosis and breast lesions [2]. However, this technique has mainly been limited to microscopic strain levels. Using indentation of a silicone gel soft tissue phantom the current study presents the combination of a fast SPAMM tagged MRI sequence and MRE for the analysis of the large strain and non-linear mechanical behavior of soft tissue.

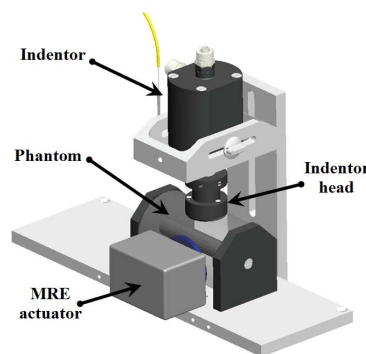


Fig 1: The indenter, soft tissue phantom and MRE actuator

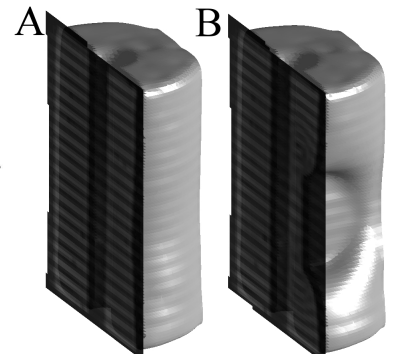


Fig 2: Iso-surface of the phantom in the initial (A) and deformed configuration (B)

**Materials and methods:** *Experimental set-up: indenter and soft tissue phantom.* Using an MRI compatible indenter (Fig 1) a silicone gel soft tissue phantom (Fig 1 and 2) was subjected to quasi-static transverse indentation (15 mm). The phantom (120 mm long, 80 mm in diameter containing stiff central core 20mm in diameter) gel is isotropic and has similar MRI properties [1] and stiffness to human soft tissue [3] and presents with a mild degree of non-linear stress-strain behavior. Figure 1 shows iso-surfaces of the phantom and the circular indentation site.

*MRI based measurement of 3D soft tissue deformation and shear modulus.* The 3D soft tissue deformation resulting from the indentation was measured using the SPAMM tagged MRI methods outlined in [1]. In addition the shear modulus was measured in both the initial and deformed configuration using MRE [3]. The scans were performed on a 3.0 Tesla Philips Intera scanner using two FLEX-M coils. The SPAMM tagged MRI data was acquired in 3 orthogonal directions (see grayscale slices in Fig. 2) and 3D Transient Field Echo readouts (scan parameters:  $T_R/T_E=2.38/1.15$  ms, flip angle  $8^\circ$ , field of view  $120 \times 120 \times 39$  mm, 26 slices, voxel size  $0.94 \times 0.94 \times 1.5$  mm, acquisition matrix  $80 \times 52$ ). The silicone gel shear modulus was estimated following MRE in the initial and deformed configuration using a spin-echo based echo-planar sequence (scan parameters:  $T_R/T_E=500/57$  ms, field of view  $128 \times 128 \times 14$  mm, 7 slices, voxel size  $2 \times 2 \times 2$  mm, acquisition matrix  $64 \times 64$ ). An MRE actuator (Fig 1, excitation frequency 50Hz) was placed laterally to the phantom (right side in Fig 3).

*Analysis of shear modulus non-linearity.* Using the measured 3D displacement the shear modulus data in the initial configuration could be warped to represent an artificial deformed configuration. This warped initial data set could then be compared to the measured deformed data set to study the effect of the indentation on the measured shear modulus.

**Results and Discussion:** Tag surfaces (Fig. 3A) were segmented using a sheet marching algorithm and tracking of their intersection points from the initial un-deformed to the deformed configuration allowed derivation of a 3D displacement vector field (Fig. 3B). This enabled the computation of deformation gradient and strain tensors (Fig 3C displays the octahedral Green-Lagrange strain which was chosen for visualization purposes). The shear modulus data for the initial and deformed configuration are shown in Fig 3D and 3E respectively. Using the displacement field in Fig 3B the initial shear modulus data could be warped to represent an artificial deformed configuration (Fig 3F). This allowed for comparison to the measured shear modulus data in the deformed configuration. Due to the mild non-linearity of the silicone gel the mean shear modulus increased from 1.65kPa (standard deviation 0.78kPa) to 1.90kPa (standard deviation 0.65kPa) following indentation. A two-tailed paired t-test showed that the means differed significantly (95% confidence level 0.16–0.33kPa,  $p=4.5 \times 10^{-8}$ ).

**Conclusion:** The current study presents the combination of SPAMM tagged MRI with MRE. This approach allows for the combined measurement of macroscopic 3D strain and shear modulus data thus providing added contrast capabilities (e.g. images representing change of elasticity parameters with respect to strain). In addition it enables the non-invasive analysis of non-linear material behavior. To the author's knowledge this is the first study to combine the two modalities for the analysis of large strain and non-linear mechanical behavior of soft tissue.

## References

[1] Moerman, K.M. et al. ISMRM ESMRMB Joint Annual Meeting, (Stockholm, Sweden, 2010), [2] Sinkus, R. et al. Magnetic Resonance in Medicine, 2005;53:372–387, [3] Moerman, K.M. et al. Journal of Biomechanics. 2009 42(8): p.1150-1153.

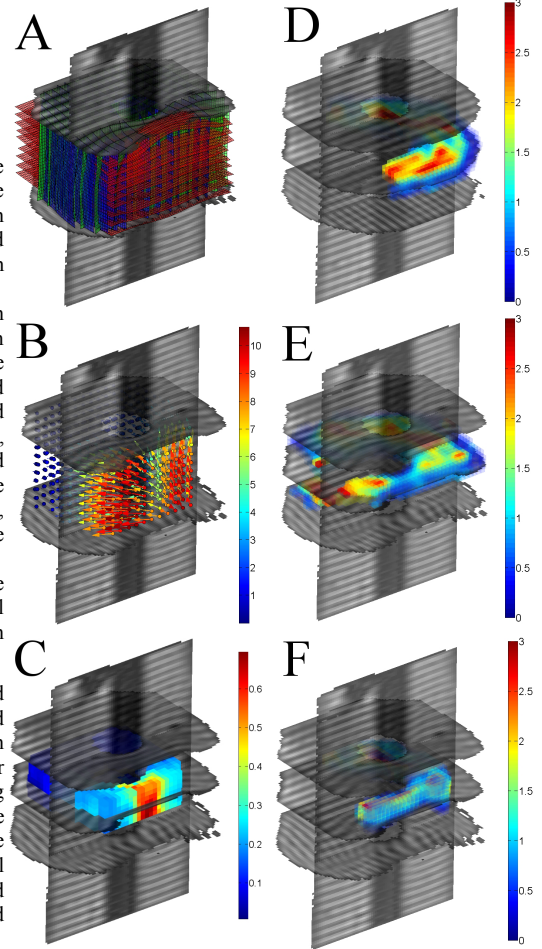


Figure 3. The segmented tag surfaces (A), the derived displacement (mm) vector field (B) and (octahedral Green-Lagrange) strain (C), the MRE derived shear modulus (kPa) in the initial (D) and deformed configuration (E) and the warped initial shear modulus data (F).