Validation of Fast Dynamic SPAMM Tagged MRI Based Measurement of Non-linear 3D Soft Tissue Deformation

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Introduction: The MRI based measurement of dynamic 3D deformation of soft tissue *in-vivo* is relevant to many areas of research such as cardiac biomechanics, the assessment of tumor motion and preoperative planning. Furthermore, when combined with inverse analysis, it enables the non-invasive determination of the mechanical properties of human soft tissue [1]. The current study uses SPAtial Modulation of the Magnetization (SPAMM) for measurement of dynamic 3D soft tissue deformation. Current SPAMM methods typically construct data from many repeated motion cycles. This has so far confined their application largely to the analysis of highly repeatable and periodic movements (e.g. the heart), but discomfort and health issues frequently preclude a large number of repetitions. The current study presents the validation of a novel fast SPAMM sequence for the measurement of dynamic 3D soft tissue deformation following just 3 repeated motion cycles. The deformation measurements were validated using marker tracking in a silicone gel phantom.

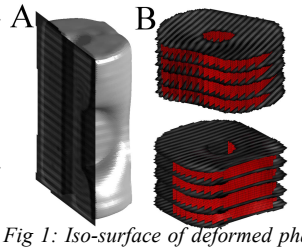

Fig 1: Iso-surface of deformed phantom (A) tag surfaces segmentation (B)

Materials and methods: *The validation set-up: indentor and soft tissue phantom.* Using an MRI compatible indentor [1-3] a cylindrical silicone gel soft tissue phantom (120 mm long, 80 mm in diameter, containing rigid core 20mm in diameter, Fig 1A) was subjected to repeated dynamic transverse indentation (15 mm, 10mm/s). The gel has similar MRI [2] and mechanical properties [1] to human soft tissue and contains contrasting spherical markers (3±0.05 mm in diameter) which can be automatically tracked at high accuracy (error <0.06 mm [3]) to provide a reference measure of 3D deformation.

MRI sequence design. The complex 3D soft tissue deformation resulting from the indentation was measured using the SPAMM tagged MRI methods outlined in [2]. A (non-ECG triggered) SPAMM sequence was used whereby a single 1-1 (first order) SPAMM pre-pulse imposes a sinusoidal modulation on the magnetization, the distortion of which can be directly related to the motion that occurred between the delay (123ms) introduced between the pre-pulse (5ms) and readout (177ms). SPAMM sets were acquired following single 3D Transient Field Echo (TFE) read-outs (T_R/T_E=2.4/1.17 ms, flip angle 8˚, field of view 120x120x39 mm, voxel size 0.94, 0.94, 1.5 mm, acquisition matrix 80x52, 26 slices). Full 3D deformation measurement is achieved using dynamic measurements (6 dynamics see Fig 2) for 3 repeated motion cycles each acquired with mutually orthogonal SPAMM directions. For validation purposes, marker movements were tracked from T2-weighted scans (0.5 mm isotropic) of the same field of view for the initial and final deformed configuration. All scans were performed on a 3.0 Tesla Philips Intera scanner using two FLEX-M coils.

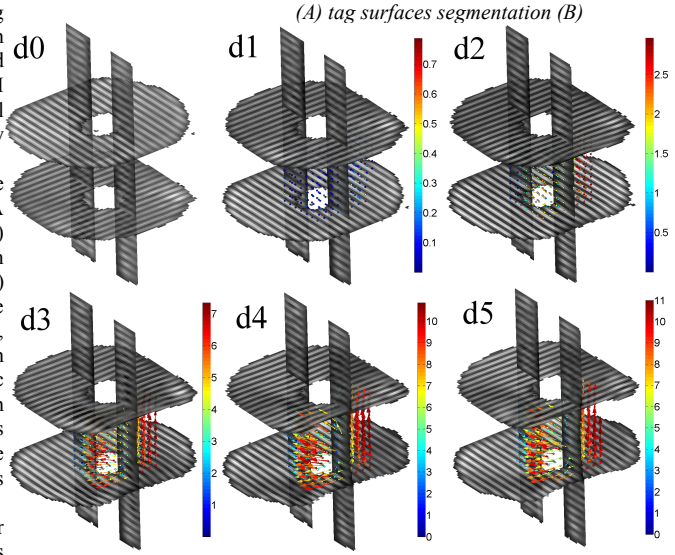

Fig 2: The 6 dynamics from initial (d0) up to final (d5) showing SPAMM tagged MRI slices for each of the 3 directions and the derived (cumulative) 3D displacement field (units mm)

Deriving and comparing deformation from the MRI data. To derive 3D displacement for each dynamic step, a sheet-marching algorithm [2] was used to segment the tag surfaces (see example in Fig 1B). The intersections of these surfaces provided a 3D grid of trackable points and thus displacement measurement for each dynamic. The 3D displacement for each dynamic was then combined to form a continuous deformation from the start to the end of the motion cycle. The marker locations in the T2-weighted scans were determined using the methods outlined in [3]. Using the SPAMM derived displacement field the marker locations in the deformed configuration can be predicted and compared to the true measured locations for validation. Due to the dynamic nature of the scans, the motion continued during the read-out. Since SPAMM tags present with specific k-space features (i.e. peaks) the timing of the acquisition of these features affects the resulting appearance, magnitude and apparent timing of the motion measurement. Depending on the SPAMM pattern and k-space acquisition strategy applied, a certain percentage of the read-out can be identified at which the SPAMM features are predominantly defined. The motion occurring during the remaining percentage might thus not be significantly reflected in the data. For the current study it was assumed that the displacement can be scaled towards the end of the read-out to account for this missing motion and the amount of scaling required was determined by minimization of the error with respect to marker displacement.

Results and Discussion: Using a sheet-marching algorithm, tag surfaces were segmented for each SPAMM direction. Tracking of tag surface intersections for each dynamic step allowed for measurement of 3D displacement for each dynamic and could be combined to form the total (with respect to initial) displacement vector fields (Fig 2) and the relative (with respect to the previous dynamic) displacement vector fields (Fig 3A). The curved motion paths and the varying magnitude with time demonstrate the non-linearity of the motion and its history. The blue points in Fig 3B represent the measured initial marker locations (n=10). Using the SPAMM derived displacement the marker locations in the final deformed configuration could be predicted (red points in Fig 3B) and compared to the true final marker locations (green points in Fig 3B). If no (temporal) scaling is applied the mean displacement difference was 0.27 mm (standard deviation 0.61 mm). However, due to the SPAMM pattern and k-space acquisition strategy used in the current study, the SPAMM pattern was predominantly defined at 86% of the read-out and thus, by taking this into account via temporal scaling, the mean displacement difference was further reduced to 0.08 mm (standard deviation 0.63 mm).

Conclusion: A novel SPAMM tagged MRI and post-processing framework for the dynamic measurement of non-linear 3D soft tissue deformation following just three repeated motion cycles has been presented. The techniques were validated using marker tracking in a silicone gel phantom and demonstrated a mean displacement difference of 0.08mm (standard deviation 0.63mm). Since only 3 motion cycles are required (1 for each orthogonal SPAMM direction) the presented methods are, to the author's knowledge, the fastest currently available for the dynamic measurement of non-linear 3D soft tissue deformation.

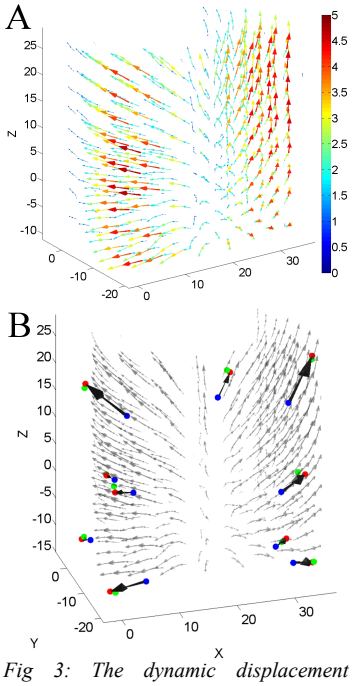

Fig 3: The dynamic displacement vectors (A-B) and the true initial (blue), true final (green) and predicted final (red) marker locations (B) (units mm).

References: [1] Moerman et al. Journal of Biomechanics. 2009 42(8): p.1150-1153., [2] Moerman et al, ISMRM ESMRMB Joint Ann. Meeting, (Stockholm, Sweden, 2010), [3] Moerman et al, EURASIP Journal Adv. Sig. Proc. 2010.