Model-Based Estimation of 3D Myocardial Motion Based on Cine DENSE MRI

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Introduction: Multi-slice or 3D cine Displacement Encoding with Stimulated Echoes (DENSE) can acquire displacement-encoded images representing the 3D motion of the entire left ventricle with high spatial resolution and accuracy relative to SPAMM tagging, but still with finite signal-to-noise ratio and finite spatiotemporal sampling. The goal of this project was to develop a technique in which a patient-specific 3D model was employed to improve DENSE estimates of the continuous spatiotemporal displacement field throughout the 3D boundaries of the left ventricle.

Methods: MRI was performed on 5 normal volunteers using a 1.5T system (Avanto, Siemens Medical Solutions, Malvern, PA) and a cardiac phased array RF coil. Each exam consisted of localizers and a complete set of slices (10-12 short axis and 3 long axis) covering the entire left ventricle using an ECG-gated breathhold 2D spiral cine DENSE sequence (1). The 2D DENSE images were encoded for displacement in 3 orthogonal directions, so that the 3D displacement of each voxel throughout the left ventricle could be estimated. Imaging parameters included: 2.5x2.5x8mm voxel size, TR 18ms, and TE 2 ms, yielding 18 – 22 cardiac phases/slice. Five 2D-SPAMM images (3 short axis and 2 long axis) were also collected (tag spacing 8mm, tag width 2mm) and used to verify the accuracy of the model. The acqusition time for each cine DENSE slice was ~20 seconds, and the total exam time was ~1 hour.

For each complete DENSE data set, a cardiac-specific geometric model was constructed in a prolate spherical coordinate system from contoured magnitude-reconstructed images at single cardiac phase, as described by Nielson et al. (2). The model consisted of 16 bicubic Hermite elements. Once a model of the ventricular geometry was defined, the material coordinates, $\mathbf{X}_0(\varepsilon)$, of each voxel in the DENSE images within the model were computed and a continuous displacement field, u(ε,t), was estimated by minimizing the objective function

$$\mathbf{x}_n = \underset{\hat{\mathbf{x}}=\mathbf{x}_n\psi_n}{\arg\min}_{\hat{\mathbf{x}}} E(\hat{\mathbf{x}}) = \sum_{i=1}^{M} \frac{1}{\sigma_i} \left| \hat{\mathbf{x}}(\varepsilon_i, t) - \mathbf{y}_i^t \right|^2 + \int_\Omega \omega(\hat{\mathbf{x}}(\varepsilon,t)) \partial\varepsilon \partial t$$

where $\hat{\mathbf{x}}(\varepsilon,t) = \mathbf{X}_0(\varepsilon) + \mathbf{u}(\varepsilon,t)$

where $\mathbf{x}(\varepsilon,t)$ is a continuous function representing material locations in space and time; and $\mathbf{y}_i^t$ is the material location for the i^{th} measurement at time, t. The second term of the objective function, $\omega(\mathbf{x})$, added constraints to the space of viable displacement fields within the volume, Ω. A weighted Sobelov norm and/or appropriate material constraints, such as on the deformation gradient tensor, were used for this term (3). In general, given the density of DENSE data no Sobelov smoothing was needed. The material locations, $\mathbf{x}(\varepsilon,t)$, were interpolated within each element using tricubic Hermite shape functions along the three coordinate directions and a fifth order Lagrange polynomial in time. The objective function was minimized using custom MATLAB (Mathworks, MA) code with the constrained solver SQPLab (4). This approach is similar to the previous use of a 3D model to analyze tagged MR data (3); however important improvements are that (a) the density of the measured DENSE displacement data is an order of magnitude higher than the density of displacement data from conventional tagging, (b) the higher density data enabled much less smoothing and fewer model constraints (i.e., we did not have to assume that the transmural variation of displacements was linear), and (c) limitations in tagging estimates of through-plane motion are eliminated using DENSE encoded for 3D motion.

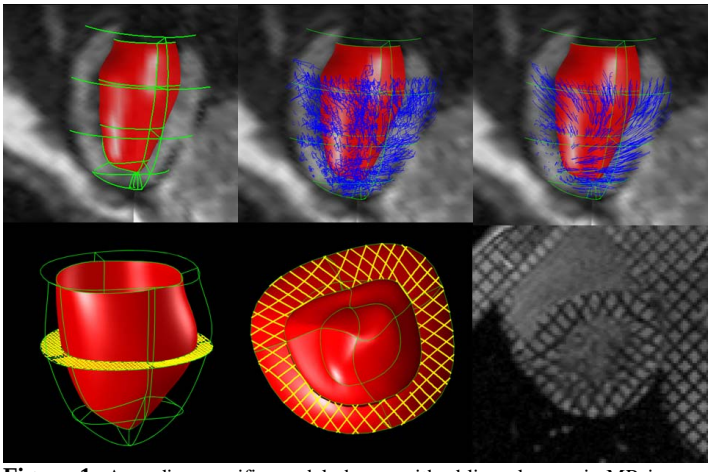

Figure 1. A cardiac specific model shown with oblique long axis MR images (top left) and raw displacement vectors (top middle). Once the model is fitted, material locations at high spatial and temporal locations may be determined (top right). Mid-ventricular synthetic tags (yellow) are computed in the diastolic phase (bottom left). A short axis zoomed version of these tags (bottom middle) agree closely with the corresponding SPAMM image (bottom right) taken at mid systole. Note the apical twist that is captured well in the model (bottom middle)

The model was verified by using it to compute locations of synthetic tag lines at various intervals throughout the cardiac cycle and comparing these synthetic tags to the acquired SPAMM-tagged MR images.

Results: Figure 1 (top row) depicts the fitting process for a sample patient**.** The average displacement error measured as the root mean squared distance between the interpolated displacement field and each DENSE measurement was <2.5 mm, which is smaller than the pixel size of 2.5x2.5x8mm and lower than previous tagging results (3). Figure 1 (bottom row) shows excellent agreement between synthetic tag lines computed by the model (at approximately the spatial resolution of conventional tagging) and acquired SPAMM-tagged images. Figure 2 depicts renderings of the longitudinal and circumferential displacements throughout the left ventricular volume for a sample patient. As anticipated, significant transmural variation of circumferential displacement is observed. The total time to analyze a 3D data set was approximately 1.5 hours.

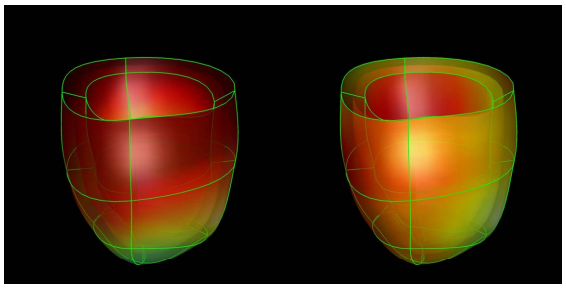

Figure 2. Rendering of the longitudinal (left) and circumferential (right) displacements on the epicardial, mid-wall, and endocardial surfaces. Red areas indicate large displacements whereas blue indicates no displacement

Conclusions: Cine DENSE MRI enables the development of 3D models of myocardial motion that are not subject to the limitations of lower resolution displacement data acquired using conventional tagging. The resultant model-based estimation of myocardial motion may provide more accurate and complete data describing the 3D mechanics of the left ventricle. The more automatic analysis of DENSE data (5,6) compared to tagging results in the ability to perform the model-based analysis relatively quickly. Applications of these methods will be to quantify 3D strains, torsion and other metrics of tissue mechanics throughout the left ventricle from cine DENSE images of human patients and animal models of human disease.

References

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