Myocardial Tissue Tracking Using Volumetric Cine DENSE with Three-dimensional Displacement Encoding: Development and Preliminary Results

X. Zhong[1], B. S. Spottiswoode[2], and F. H. Epstein[1,3]

[1]Biomedical Engineering, University of Virginia, Charlottesville, Virginia, United States, [2]MRC/UCT Medical Imaging Research Unit, University of Cape Town, Cape Town, Western Cape, South Africa, [3]Radiology, University of Virginia, Charlottesville, Virginia, United States

Introduction. Displacement encoding with stimulated echoes (DENSE) is a quantitative myocardial wall motion imaging technique that encodes tissue displacement into the phase of the stimulated echo (1). 2D cine-DENSE provides a time series of pixel-wise displacement and strain measurements for one slice, and has been previously validated for myocardial motion tracking and myocardial function evaluation (2,3). By incorporating 3D volume imaging and through-plane encoding in the cine DENSE sequence, we demonstrate the ability to extend DENSE motion tracking to seven dimensions: the voxel's position coordinates in three dimensions, the voxel's motion relative to the initial position in three dimensions, and the time dimension. This work was evaluated in healthy volunteers.

Methods. An ECG-gated 3D cine DENSE sequence was implemented using a stack-of-spirals trajectory to sample the 3D k-space with reduced motion artifact and high efficiency (4). In order to achieve suppression of artifact-generating echoes in 3D k-space, 3-point phase cycling was employed (5). The spiral gradient waveforms were designed with a maximum amplitude of 8.00 mT/m to meet the desired specifications. Single-shot images with two different TEs were acquired for each slice in the 3D slab and at each cardiac phase to estimate field maps for deblurring. The DENSE displacement-encoding gradients were designed using the shortest available time and, whenever possible, the unencoding gradients were combined with phase encoding gradients in the slice direction to achieve a short TE. Optimized fat suppression pulses were applied prior to the displacement-encoding pulses with little time penalty (6). Gridding and linear inhomogeneity compensation for spiral images, as well as DENSE data reconstruction, were performed on-line. In accordance with protocols approved by our institutional review board, and with informed consent, 3 healthy volunteers were imaged on a 1.5T MRI system (Avanto, Siemens Medical Solutions, Germany). The imaging parameters include voxel size = $2.5 \times 2.5 \times 3.0$ mm^3, slab thickness = 36 mm, flip angle = 20°, TR = 18 ms, TE = 2.1 ms, total slices in slab = 12, number of interleaves = 6, interleaves scanned per heartbeat = 2, and cardiac phases = 16. A displacement encoding frequency of 0.1 cycles/mm was used to encode in all three directions. The volunteers were scanned during free breathing, and 3 averages were performed to reduce artifacts due to respiration motion. The total scan time was approximately 30 minutes, depending on heart rate. Segmentation was done semi-automatically (7) using the overall magnitude image for each slice, which was calculated by square root of the sum of squared x-, y-, and z-encoded magnitude images. Making the simplifying assumption that the through-plane motion of all voxels of each slice in the slab is relatively uniform, Lagrangian displacement of each voxel was tracked slice by slice in 3D through all the cardiac phases for all cine DENSE data, as described in (7).

Results. Example 3D mid-level short-axis data from the left ventricular of one volunteer is shown in Fig. 1. Four adjacent slices are stacked in the long-axis direction and the space in between is scaled for better visualization. Each point in Fig. 1(A) represents the center of a voxel at end-diastole, and (B) and (C) show the positions of these points along their trajectories in 3D space at two different time points during systole, respectively. The through-plane motions are observed, and the radial thickening and circumferential shortening are seen in the recognizable tag-like deformation pattern of each slice. The corresponding in-plane motion of one slice, which is marked by the arrow in the 3D view in Fig. 1(A), is shown in Fig. 1(D-F), respectively.

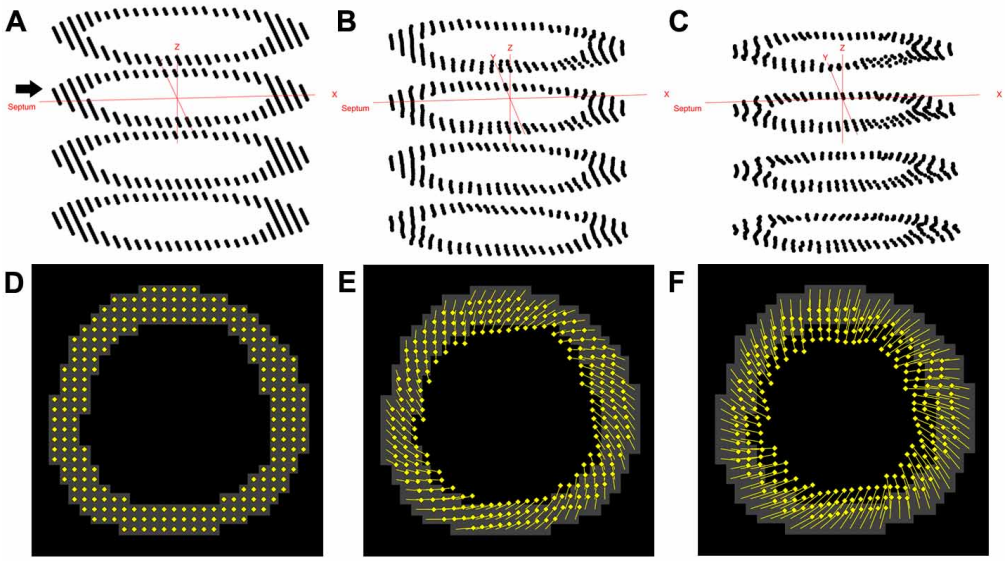

Fig 1. (A-C) The 3D trajectory positions of four adjacent slices of mid left ventricle. (D-F) The 2D trajectory positions of one slice (marked by arrow in A). The columns, from left to right, correspond to end-diastole, and two different time points during systole, respectively.

Conclusions. Cine DENSE volume imaging allows 3D myocardial motion to be tracked at a resolution equal to the voxel size. Therefore, seven-dimensional information can be resolved with nearly isotropic resolution. Initial experience in volunteers using cine DENSE volume imaging suggests that it is now possible to quantify 3D intra-myocardial motion. Future developments will include using navigator echoes for better suppression of respiratory artifact, more accurate tissue tracking of Lagrangian motion in the long-axis direction, and 3D strain tensor calculation.

Acknowledgements. Supported in part by NIBIB grant RO1 EB 001763.

1. Aletras et al. JMR 1999;137:247-252. 2. Kim et al. Radiology 2004;230:862-871. 3. Gilson et al. MRM 2004;51:744-752.
4. Meyer. Spiral Echo-Planar Imaging . In: Echo-Planar Imaging: Theory, Technique, and Application, eds. 1998.
5. Callot et al. MRM 2003 ;50:531-540. 6. Fahmy et al. JCMR 2005;7(1):524. 7. Spottiswoode et al. IEEE-TMI; in press.