Multi-Slice DENSE with Three Dimensional Displacement Encoding: Development and Application in a Mouse Model of Myocardial Infarction

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Introduction: Displacement-encoded imaging with stimulated echoes (DENSE) [1] has been used to measure short-axis 2D myocardial strain in normal and post-infarct mice [2]. However, since the heart contracts both along its short axis and its long axis, a more comprehensive measurement of myocardial function would be three dimensional (3D). The purpose of this study was to develop a multi-slice DENSE sequence with 3D displacement encoding and use it to measure 3D myocardial mechanics at high spatial resolution in normal and post-infarct mice.

Methods: A multi-slice DENSE pulse sequence [3] was developed on a 4.7 T scanner to study systolic function. Briefly, following detection of an ECG trigger pulse at end diastole, non-selective displacement encoding was performed to spatially modulate the magnetization and store it longitudinally. After a delay time to end systole, a slice-selective gradient echo readout with a DENSE unencoding gradient was used to sample the longitudinal magnetization. During the next 2 cardiac cycles, a similar readout scheme was used to sample the magnetization at end systole for 2 other slices. The sequence was designed to apply the displacement-encoding gradient along the frequency-encoding direction for in-plane imaging and along the slice-select direction for through-plane imaging. For in-plane imaging, displacement encoding was performed in two orthogonal directions by swapping the direction of frequency encoding. Phase reference data with no displacement encoding was also acquired.

Three distinct echoes are present in a DENSE experiment: the desired displacement-encoded echo and two artifact-generating echoes (a complex conjugate echo and an echo due to T1-relaxation). We employed cosine and sine modulation to eliminate (CANSEL) [4] these artifact-generating echoes independent of displacement-encoding strength and displacement-encoding direction. This approach enabled the measurement of through-plane as well as in-plane displacement of short-axis slices.

Three C57Bl/6 mice were imaged using multi-slice DENSE at baseline (Bsl) and one day (D1) after a 1hr occlusion of the LAD. During imaging, mice were anesthetized using 1% isoflurane in O_2, temperature was maintained at 37°C, and heart rate was continuously monitored. Imaging was performed using a quadrature RF coil and ECG gating. Three end-systolic short-axis images (basal, mid-ventricular, and apical) were acquired spanning approximately two-thirds of the mid-ventricle. Imaging parameters were FOV=30mm, matrix=128x128, thickness=1mm, gap=0.5mm, flip angle=90°, TE=3.1ms, TR=800ms, and averages=2. The displacement-encoding strength was 0.64-0.85 cycles/mm for in-plane imaging and 0.5 cycles/mm for through-plane imaging. On D1, additional T1-weighted FLASH images for the selected slices were acquired 20 min after an IP injection of Gd-DTPA (0.6 mmol/kg) to identify the infarcted myocardium. The parameters for Gd-enhanced imaging were similar to DENSE, except TR ~ 130 ms (1 R-R cycle).

DENSE raw data were combined as described in Ref. [4] to suppress the complex conjugate and T1-relaxation echoes. Magnitude- and phase-reconstructed images were created from the combined raw data. The phase-reconstructed images were background phase corrected, combined, and used to compute 3D displacement maps. For each slice, radial (Err) and circumferential (Ecc) strains were computed from 2D in-plane displacements using finite element methods. Net twist angle and torsion were also computed for each animal. Gd-enhanced images were used to define the D1 myocardium as infarcted or remote.

Results: A spatially sub-sampled vector map of 3D systolic displacement in basal, mid-ventricular, and apical short-axis slices of a normal mouse is shown in Figure 1. Mean displacements, twist angle, Err and Ecc for Bsl mice are summarized in Table 1. End-systolic torsion from linear regression of net twist angles was 1.37±0.16°/mm for Bsl data and -0.16±0.11 for D1 data. On D1, regions of infarcted tissue exhibited significantly reduced ($p<0.01$) radial displacement (0.05±0.09 mm), Err (0.03±0.10), and Ecc (0.04±0.03). Also, radial displacement and Ecc were significantly depressed in D1 remote myocardium (0.23±0.11 mm and -0.10±0.02, respectively, $p<0.01$). Reduced longitudinal displacement was observed on D1 both in infarcted and remote myocardium. Total scan time was approximately 50 min. per mouse.

Discussion and Conclusions: Three-dimensional displacement-encoded multi-slice MRI can provide a comprehensive measurement of myocardial mechanics in mice at 4.7T in less than 1 hour. Myocardial strains agree well with previously published values in mice [5]. Net twist and torsion are also similar to those previously reported [6]. Three dimensional displacement-encoded multi-slice MRI should prove useful for studying myocardial function in transgenic and knockout mouse models of ischemic heart disease.

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Table 1. Comprehensive Assessment of Myocardial Mechanics in Normal Mouse Hearts (mean±std)

	Base	Mid-Ventricle	Apex
Radial Displacement (mm)	0.37±0.06	0.38±0.04	0.31±0.06
Circumferential Displacement (mm)	0.06±0.03	0.15±0.02	0.21±0.06
Longitudinal Displacement (mm)	-0.58±0.11	-0.39±0.19	-0.08±0.29
Net Twist Angle (°)	1.1±0.3	2.6±0.2	5.2±1.1
Radial Strain (Err)	0.36±0.05	0.36±0.04	0.23±0.12
Circumferential Strain (Ecc)	-0.15±0.01	-0.14±0.01	-0.14±0.03

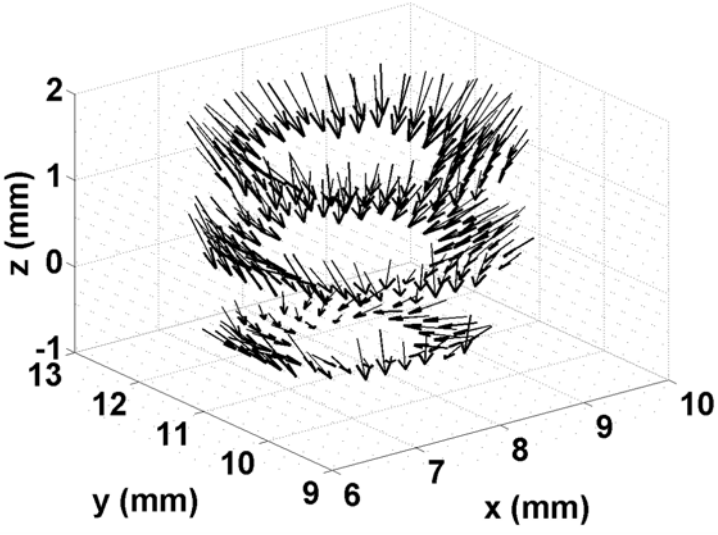

Figure 1. 3D vector map of systolic displacement in basal, mid-ventricular, and apical short-axis slices of a normal mouse heart.