Imaging 3D Myocardial Motion with SSFP Cine DENSE

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Introduction: Displacement-encoding with stimulated echoes (DENSE) (1) is a quantitative method for imaging intramyocardial motion with high spatial resolution and without the need for tag detection inherent to conventional myocardial tagging. Previous implementations of DENSE have measured the two-dimensional (2D) in-plane components of motion. However, a limitation of short-axis imaging with 2D DENSE is that the longitudinal motion of the heart is not taken into account. The purposes of this study were to develop a cine DENSE method for measuring through-plane motion and to use it in conjunction with in-plane displacement imaging to map 3D myocardial motion.

Methods: An ECG-gated SSFP sequence was modified for in-plane or through-plane DENSE imaging on a 1.5T Siemens Sonata scanner. As in SSFP myocardial tagging (2), upon R-wave detection, an α/2 storing pulse was used to interrupt the steady state. After applying displacement-encoding pulses in an in-plane or through-plane direction, a second α/2 pulse was used to approximately restore the steady state. During data acquisition, a displacement unencoding gradient was applied in the appropriate direction and other gradient pulses were adjusted to maintain SSFP requirements on gradient moments. To suppress DENSE artifacts in a manner that is independent of displacement-encoding direction, displacement-encoding frequency, and time, cosine and sine modulated data were acquired to eliminate (CANSEL) extraneous echoes (3). Phase reference images without displacement encoding were also acquired. Two breathholds were used to acquire cine DENSE images measuring through-plane motion, and additional breathholds were used for cine DENSE images encoded for motion in each in-plane direction. Therefore, the time-varying 3D displacement of each slice of myocardium was imaged in four breathholds.

During image computation, raw data were combined according to the CANSEL reconstruction algorithm (3) and then Fourier Transformed to create magnitude and phase images. After phase correction using phase reference data, displacements were computed from the phase-reconstructed images and combined to create 3D displacement maps.

Phantom and volunteer studies were performed using the modified SSFP cine DENSE sequence. Specifically, for phantom validation studies coronal images of an agarose gel phantom rotating about the longitudinal axis of the magnet were acquired using cine DENSE encoded for through-plane displacement. Through-plane displacement of the phantom measured by DENSE was compared to the predicted displacement, where the predicted displacement was computed using the pixel location and the frequency of rotation of the phantom. *In vivo* validation studies were also performed by comparing short-axis cine DENSE images encoded for through-plane displacement to long-axis images acquired with conventional myocardial tagging applied perpendicular to the longitudinal axis of the heart. The *in vivo* studies were performed in three normal volunteers where longitudinal myocardial motion was assessed at basal, midventricular, and apical levels. In addition to imaging through-plane motion, cine DENSE images encoded for in-plane motion were acquired, resulting in measurement of the time-varying 3D displacement of the heart. Imaging parameters included: FOV = 360 mm, matrix = 128 x 96, slice thickness = 8 mm, TR = 3.8 ms, TE = 1.9 ms, flip angle = 25°, segments =16, cardiac phases =16, and displacement encoding frequency = 0.5 cycles/cm.

Results: Cine DENSE measured through-plane displacement with high accuracy in the rotating phantom as demonstrated in Fig. 1, where displacement as a function of spatial position across the phantom is plotted with measured values shown as colored dots and predicted values shown as gray lines. The different colors represent displacement at different phases of rotation, mimicking different cardiac phases. Magnitude-reconstructed short-axis DENSE images of volunteers had high signal-to-noise ratio (25.1 ± 4.3), and measurements of through-plane myocardial displacement from phase-reconstructed images demonstrated a gradient of longitudinal displacement from base to apex and were in agreement with measurements made by conventional myocardial tagging (Fig. 2). By combining short-axis cine DENSE measurements of through-plane and in-plane displacement, 3D cine maps of myocardial motion were computed. An example vector map of 3D end-systolic displacement in a midventricular slice of a normal volunteer is shown in Fig. 3, where base-to-apex longitudinal motion and radial motion toward the center of the left ventricle can be seen. Image artifacts were typically observed in the first image following application of the displacement-encoding pulses due to oscillation of the SSFP signal prior to signal stabilization.

Conclusions: As in SSFP myocardial tagging (2), sampling the displacement-encoded echo using an SSFP sequence provides for rapid data acquisition and high SNR. The use of storing and restoring pulses surrounding the displacement-encoding pulses confines transient SSFP artifacts to the first cardiac phase after displacement encoding. Using the CANSEL technique to suppress DENSE artifacts independent of time and the displacement-encoding direction (3) enables the accurate measurement of through-plane motion, as demonstrated by the rotating phantom experiments. Initial comparisons with long-axis myocardial tagging suggest good accuracy for *in-vivo* measurements of through-plane myocardial motion by cine DENSE. When combined with images encoded for in-plane motion, the 3D motion of the heart can be measured using these techniques.

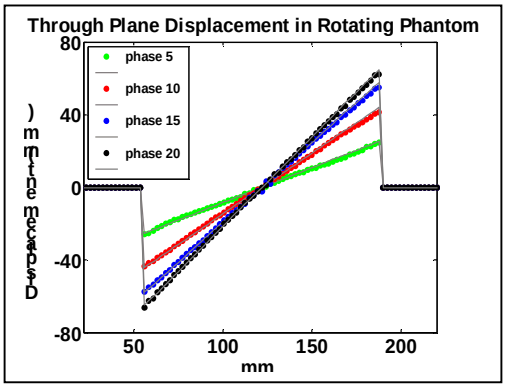

Figure 1. Measurement of through-plane motion in a rotating phantom by cine DENSE. Displacement is shown on the y-axis and position across the image is shown on the x-axis.

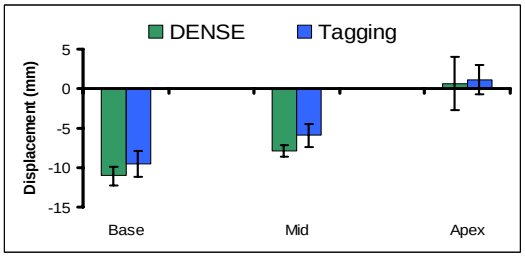

Figure 2. Longitudinal systolic displacement for basal, mid-ventricular, and apical slices as measured by short-axis DENSE with through-plane encoding and long-axis myocardial tagging.

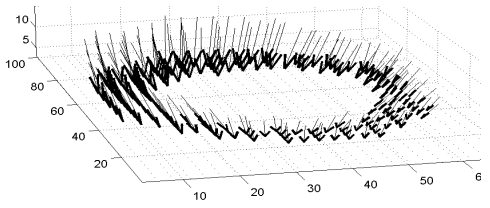

Figure 3. 3D vector map of systolic motion for a mid-ventricular short-axis slice in a normal volunteer.

1. Aletras AH, et al. MRM 2001;46(3):523-34. 2. Herzka DA, et al. MRM 2003;49(2):329-340. 3. Epstein FH, et al. Proc ISMRM 2003;11:1645.