Velocity-compensated DENSE MRI

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Introduction. Displacement encoding with stimulated echoes (DENSE) is a quantitative imaging technique that encodes tissue displacement into the phase of the stimulated echo (1). As shown in Fig. 1, DENSE is intended to measure tissue displacement occurring during the period indicated by TM, while the magnetization is stored along the longitudinal axis. However, during the displacement encoding module and the gradient echo readout module, the magnetization is in the transverse plane for periods Td and TE, respectively, and phase shifts unrelated to the desired displacement-induced shift can occur. The purpose of this study was to investigate the errors caused by tissue velocity during the periods Td and TE, where gradient pulses are applied, on DENSE displacement estimates, and to show that these errors can be eliminated using velocity-compensated (first moment nulled) gradient waveforms.

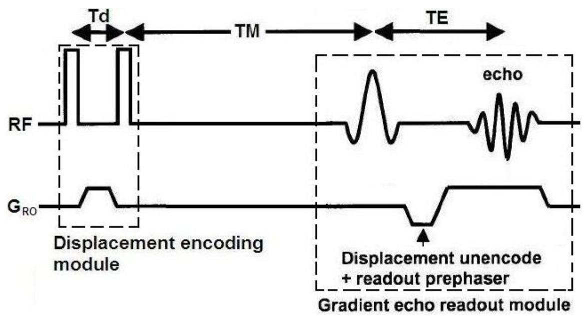

Fig. 1. Sequence timing diagram for DENSE.

Theory. Given the initial position vector $\mathbf{r_0}$ at time t = 0, and assuming the velocity vector $\mathbf{v_0}$ is constant, the accumulated phase of a spin due to the presence of a gradient centered at t = D with length L can be expressed as $\phi(t) = 2\pi k(t)(\mathbf{r_0} + \mathbf{v_0}D) + \gamma M_1(t)\mathbf{v_0}$, where k(t) is the spatial or displacement-encoding frequency introduced by this gradient, and $M_1(t) = \int_{-L/2}^{t-D} G(u+D)u\,du$ is the 1st moment of the translated copy of this gradient centered at t = 0. The accumulated phase terms due to various gradients in both modules can be divided into three cases: (a) For the prephaser of the readout gradient, the phase encoding gradient and the rewinder of the slice-select gradient, their M_1 terms equal zero, but their $\mathbf{v_0}D$ terms cause spatial misregistration of the images in the corresponding directions. (b) For the readout gradient and the slice-select gradient, both $\mathbf{v_0}D$ and M_1 terms are non-zero. The $\mathbf{v_0}D$ terms cause misregistration in the readout and slice-select directions, and the M_1 terms induce phase errors. (c) For DENSE encoding and unencoding gradients, the M_1 terms equal zero, but their $\mathbf{v_0}D$ terms induce phase errors.

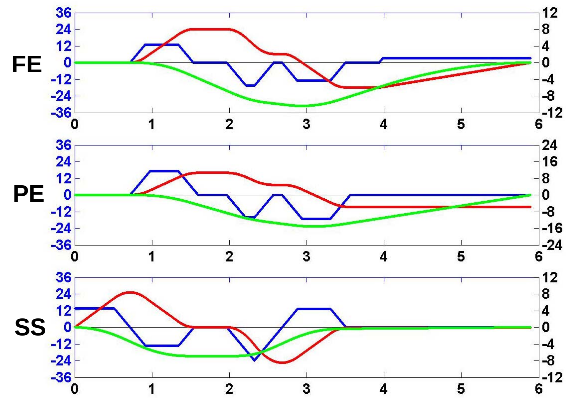

Fig. 2. Gradient echo readout module with velocity-compensated bipolar gradient pairs applied on all axes. The two lobes of the bipolar gradient pairs are separated by other gradients. The blue line is the gradient amplitude (scale on the left in G/cm), the red line is the 0th moment, and the green line is the 1st moment (scale on the right in ms^2·G/cm). The time scale is in ms.

Methods. A DENSE sequence (2) was modified such that bipolar velocity-compensated gradient waveforms were applied on all 3 axes in the displacement encoding module (time starts at the center of the first 90° RF pulse, and the 1st moment is nulled at the center of the second 90° RF pulse) and in the gradient echo readout module (time starts at the center of the excitation RF pulse, and the 1st moment is nulled at TE). The lobes of the bipolar gradients were separated with a delay time so that other gradients were performed in between. Another delay time Δ could be added before the readout gradient to generate more severe motion-induced effects and to fulfill the 1st moment nulling timing requirement if necessary. The same rotating phantom as described in (2) was scanned at a rotation frequency of 2.77 ± 0.02 Hz on a 4.7T MRI system (Varian, Palo Alto, CA) using DENSE with and without velocity compensation. Whenever possible, identical imaging parameters were used for scans with and without velocity compensation, which included pixel size = 0.2 × 0.2 mm^2, slice thickness = 1 mm, flip angle = 90°, displacement encoding frequency k_e = 0.3 cycles/pixel, TR = 400 ms, time between displacement encoding and the excitation RF pulse (TM) = 60 ms, and 4-point phase cycling for artifact suppression (2). Different parameters included TE = 5.6 ms (Δ = 2.4 ms) for the scan without velocity compensation, and TE = 7.9 ms (Δ = 2.0 ms) for the scan with velocity compensation. Magnitude and phase images of DENSE data were reconstructed using MATLAB. Displacements were calculated after phase unwrapping and compared with theoretical values based on position and rotation frequency. A calculation was also performed in MATLAB to validate the 1st moment nulling algorithm in the sequence.

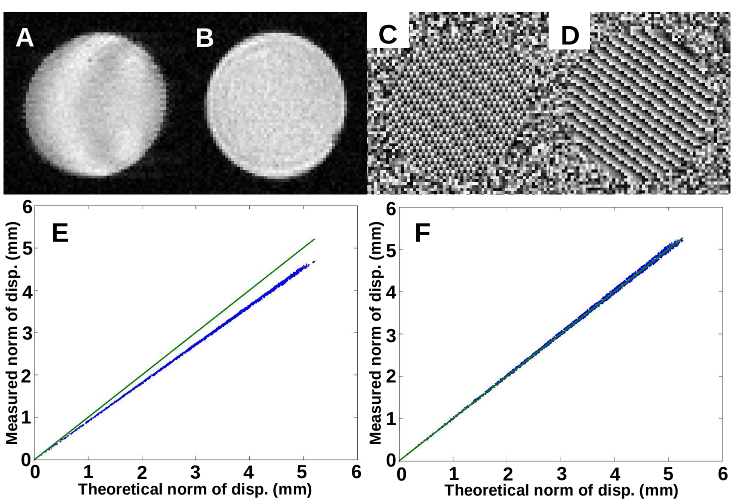

Fig. 3. Example results of a rotating phantom: magnitude (A) and phase (C) DENSE images without velocity-compensation for TE = 5.6 ms (Δ = 2.4 ms); magnitude (B) and phase (D) DENSE images with velocity-compensation for TE = 7.9 ms (Δ = 2.0 ms); and displacement measured by DENSE vs. theoretical displacement without (E) and with (F) velocity-compensation (green line is line of identity).

Results. Example calculation results of the 0th and the 1st moments for the gradient echo readout module are shown in Fig 2. The rotating phantom results are shown in Fig 3. Without velocity compensation, spatial misregistration was observed as distortion of the cylindrical phantom (Fig 3A), and phase error was observed as distortion of the phase wrapping pattern (Fig 3C). Moreover, significant error in the displacement measurement occurred (Fig 3E). In contrast, the use of velocity compensated gradients corrected the spatial misregistration artifacts (Fig 3B) and phase error (Fig 3D), and also eliminated the displacement measurement error (Fig 3F).

Discussion and conclusions. Velocity can cause misregistration and phase errors in DENSE data if not compensated for. In general, these errors are greater when the tissue velocity is higher, Td or TE is larger, and/or the gradient 1st moments are larger. For human cardiac MRI, these errors are rather small. However, for MRI of the mouse heart, the average myocardial velocity is 2 mm/100 ms, the maximal displacement is around 1 mm, and the pixel size is around 0.2 × 0.2 mm^2, which leads to approximately a 10-15% error in displacement for typical imaging parameters. These errors can be eliminated using velocity-compensated gradient waveforms.

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

1. Aletras et al. JMR 1999;137:247-252.
2. Epstein et al. MRM 2004;52:774-781.