Strain Measurements with Displacement ENcoding with Stimulated Echoes (DENSE) are Robust to Off Resonance

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Introduction: Displacement ENcoding with Stimulated Echoes (DENSE)(*1*) is used for quantitative measurements of regional myocardial displacement from which strain can be derived. The DENSE technique encodes displacement in the phase of the MRI signal. The signal phase, however, can be corrupted by local field off-resonance. The off-resonant fields are spatially non-uniform over the heart and vary during the cardiac cycle(*2*). DENSE displacement measures are subject to different off-resonant fields during position encoding at the beginning of the cardiac cycle and position de-coding prior to image acquisition. The ***objective*** of this study was to define the effects of main field off-resonance on displacement and strain measures in a DENSE experiment.

Theory: The displacement measured with the DENSE pulse sequence is encoded in the stimulated echo (STE, Eqn. 1) and the stimulated anti-echo (STAE, Eqn. 2) for the jth isochromat. One-dimensional Lagrangian strain (E) is proportional to the stretch ratio (λ) between isochromat 1 and 2. Recall, E=0.5(λ^2-1) and Eqn. 3.

$$d_{STE_j} = \frac{\nu - (\psi_f - \psi_i)}{\gamma M_0} \quad \textbf{Eqn. 1} \qquad d_{STAE_j} = \frac{\nu - (\psi_f + \psi_i)}{\gamma M_0} \quad \textbf{Eqn. 2} \qquad \lambda = \frac{p_{f2} - p_{f1}}{(p_{f2} - d_2) - (p_{f1} - d_1)} \quad \textbf{Eqn. 3}$$

Where, ν is the motion encoded phase and ψ_i and ψ_f are the off-resonance induced phase in the initial and final positions of the jth isochromat. The initial position is equal to the final position (p_{fj}) minus the total displacement (d_j). Thus, combining Eqns. 1-3 gives:

$$\lambda_{STE} = \frac{\delta p_f}{\delta p_f - (\delta\nu - \delta\psi_f + \delta\psi_i)\cdot(\gamma M_0)^{-1}} \quad \textbf{Eqn. 4} \qquad \lambda_{STAE} = \frac{\delta p_f}{\delta p_f - (\delta\nu - \delta\psi_f - \delta\psi_i)\cdot(\gamma M_0)^{-1}} \quad \textbf{Eqn. 5}$$

Where δ indicates a difference in the subsequent variable between the two isochromats in the initial or final positions.

Methods: Off-resonance effects on displacement and strain measurements were investigated using both a DENSE Bloch simulation and an analytic solution (Eqn. 1 & 2 and the strain expression derived from Eqn. 4 & 5). A DENSE encoding scheme with a sensitivity of 2cm/π, 90° flip angles and a three-point RF phase cycling scheme (0°, 120°, and 240°) was implemented for 1-D displacement and strain. The off-resonance was varied as a function of initial and final position. The difference in the off-resonance frequency between two isochromats in the initial positions varied from 0 to 1Hz. The difference in off-resonance frequency between the initial and the final positions varied from -10 to 10Hz. Off-resonance differences for isochromats in the final position were assumed to be the same as that of the initial positions. The displacement varied as ±0.5 cm and ±0.1 cm. The strain varied as ±5% and ±20%.

Results: The displacement error arising from off-resonance for the STE is <8% if ψ_i and ψ_f are nearly equal (ψ_f-ψ_I<4Hz, Fig. 1A). The displacement error for the STAE <12% under the same conditions (Fig. 1B). If ψ_i and ψ_f are nearly equal and opposite in sign then the error for the STAE is smaller than the error for the STE. When the displacement is small (1 mm) the off-resonance induced error is greater than for large displacements (5 mm). While phase is reported in Eqns. 1-5, we have graphed the off-resonance frequency in all plots.

In Fig. 1C-D the percent error in strain is plotted as a function of the difference in off-resonance frequency between the initial and final position (ω_f-ω_i) and the difference in off-resonance frequency between the initial positions ($\delta\omega_i$=$\delta\omega_f$). The strain calculated from the STE is subject to error due to $\delta\psi_i$ and $\delta\psi_f$, but these local spatial gradients in the off-resonance field are small and nearly equal in magnitude. Hence, the off-resonance terms nearly cancel in Eqn. 4. The percent error in strain is <0.2% for all values of strain (±5% and ±20%) and off-resonance, indicating that strain derived from the STE is not subject to error from off-resonance. Larger errors are present for smaller strains.

The strain calculated from the STAE is also subject to error due to $\delta\psi_i$ and $\delta\psi_f$, but these terms sum in Eqn. 5. The percent error in strain is <30% for small strains (±5%) and <10% for large strains (±20%), indicating that STAE strain is about two orders of magnitude more sensitive to off-resonance than the STE strain. Both the STE and STAE strain are relatively insensitive to differences in off-resonance between the initial and final positions.

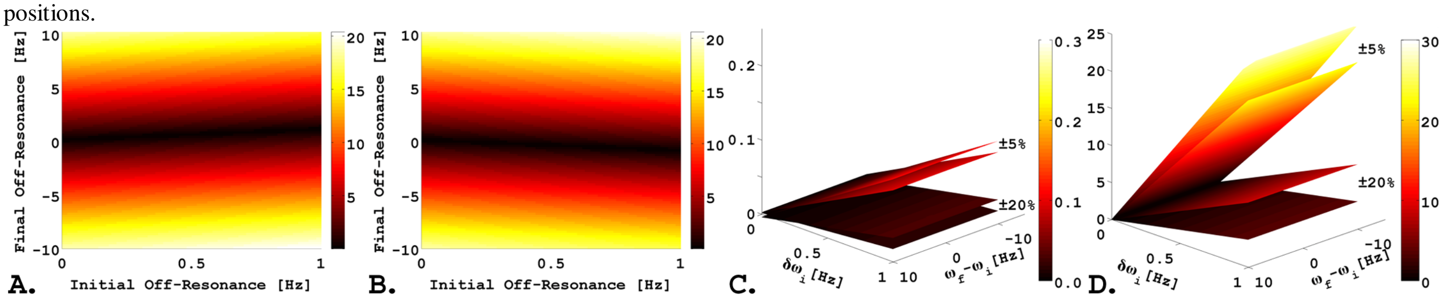

Figure 1. Percent error surfaces for displacement (A & B) and strain (C &D) for the stimulated echo (A & C) and stimulated anti-echo (B & D).

Discussion: The percent error in displacement in the STE and the STAE are affected by off-resonance differently, but produce errors of similar magnitudes. The percent error in strain calculated from the STE is insensitive to the effects of a wide range of off-resonances, whereas large strain errors can arise when using the STAE. In general, the percent error of the STE strain was lower than the displacement percent error. Strain and displacement percent error from the STAE are sensitive to off-resonance affects.

Reference: [1] A. H. Aletras et al, *J Magn Reson* **137**, 247 (Mar, 1999). [2] S. B. Reeder et al, *Magn Reson Med* **39**, 988 (Jun, 1998).

Acknowledgements: This work is supported by NIH/NHLBI to HL087614 DBE.