Improved DENSE MRI Using Balanced Multi-point Displacement Encoding

X. Zhong[1], P. Helm[2], A. Young[3], R. Kirton[4], and F. H. Epstein[1,2]

[1]Biomedical Engineering, University of Virginia, Charlottesville, Virginia, United States, [2]Radiology, University of Virginia, Charlottesville, Virginia, United States, [3]Department of Anatomy with Radiology, University of Auckland, Auckland, New Zealand, [4]Bioengineering Institute, University of Auckland, Auckland, New Zealand

Introduction. Displacement encoding with stimulated echoes (DENSE) is a quantitative myocardial wall motion imaging technique that encodes tissue displacement in the phase of the acquired signal (1). Thus, DENSE is similar to velocity-encoded phase contrast (PC), where, instead of displacement, velocity is encoded in the phase of the acquired signal. To date, various multi-dimensional DENSE sequences have encoded displacement in two or three *orthogonal* directions, and have acquired an additional image without displacement encoding for phase reference (1,2). This encoding strategy is precisely analogous to the simple multi-point method for velocity-encoded PC (3). A balanced four-point encoding strategy with improved noise variance and symmetry has been previously described for 3D velocity-encoded PC (but not for 2D PC) (3). We investigated the balanced multi-point strategy for DENSE with 2D and 3D displacement encoding. Due to the signal-to-noise ratio (SNR) dependence on displacement-encoding frequency particular to DENSE (4,5), but not on velocity encoding in PC, as well as the noise variance and symmetry properties, the balanced multi-point method may be especially advantageous for DENSE imaging.

Theory. For 2D displacement encoding, using a minimum of 3 scans, three unknowns can be computed from the phase-reconstructed images: $k_e\Delta x$, $k_e\Delta y$, and ΔE, where k_e is the spatial frequency imparted to the transverse magnetization by the displacement encoding gradients, Δx and Δy are the displacements in the x- and y-directions, respectively, and ΔE is the background phase. The simple 3-point encoding method can be expressed as Eq. [1A], where S_1, S_2, and S_3 are the phase of the stimulated echoes in the first, second, and third scans, respectively, and the square matrix on the right side is the weighting matrix for the encoding strategy. The desired displacement-encoded phase can be solved by Eq. [1B], where the square matrix on the right side is the decoding matrix. Assuming the noise is equal and uncorrelated in each scan, the variance in each phase image is $\sigma_\phi^2 = \sigma^2/|S|^2$, where σ^2 is the noise variance in the complex image, and $|S|$ is the magnitude of the signal in the voxel of interest (6). Just as for velocity-encoded PC, the noise variance of the phase image in each direction is $\sigma_{S3}^2 = \sigma_{S3x}^2 = \sigma_{S3y}^2 = 2\sigma_\phi^2$, and the covariance between $k_e\Delta x$ and $k_e\Delta y$ is $\mathrm{cov}_{S3}(x,y) = \sigma_\phi^2$ (3). For balanced encoding, the encoding directions are evenly distributed in space. In the 2D case, the encoding directions must be along the three circumradii of an equilateral triangle centered at the origin. Eq. [2A] gives a weighting matrix with one circumradius on the x axis, and the other weighting values can be obtained by calculating the vertex coordinates of this equilateral triangle. The corresponding decoding matrix is given by Eq. [2B]. An important implementation issue is that non-integer scaling of the phase angle would introduce errors if phase wrapping occurs in the phase of the stimulated echo. To avoid this problem, only integer scaling should be performed during decoding, and the residual scaling factor should be removed later when calculating the displacement. Eq. [2C] is used in practice. A disadvantage is that the resultant phase wrapping is more severe than that of the simple method. However, the noise variance of the decoded phase image in each direction is $\sigma_{B3}^2 = \sigma_{B3x}^2 = \sigma_{B3y}^2 = 2\sigma_\phi^2/3$, which is only one third of the noise variance of the simple 3-point method. The covariance between $k_e\Delta x$ and $k_e\Delta y$ is $\mathrm{cov}_{B3}(x,y) = 0$. So, unlike the simple 3-point method, the balanced 3-point method has independent noise in the measured $k_e\Delta x$ and $k_e\Delta y$.

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} k_e\Delta x \\ k_e\Delta y \\ \Delta E \end{bmatrix}$$
Eq. [1A]

$$\begin{bmatrix} k_e\Delta x \\ k_e\Delta y \\ \Delta E \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 \\ -1 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}$$
Eq. [1B]

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -1/2 & \sqrt{3}/2 & 1 \\ -1/2 & -\sqrt{3}/2 & 1 \end{bmatrix} \begin{bmatrix} k_e\Delta x \\ k_e\Delta y \\ \Delta E \end{bmatrix}$$
Eq. [2A]

$$\begin{bmatrix} k_e\Delta x \\ k_e\Delta y \\ \Delta E \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & \sqrt{3}/3 & -\sqrt{3}/3 \\ 1/3 & 1/3 & 1/3 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}$$
Eq. [2B]

$$\begin{bmatrix} 3k_e\Delta x \\ \sqrt{3}k_e\Delta y \\ 3\Delta E \end{bmatrix} = \begin{bmatrix} 2 & -1 & -1 \\ 0 & 1 & -1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix}$$
Eq. [2C]

These concepts can be straightforwardly extended to the 3D case. For the simple 4-point method, the noise variance of the phase image in each direction can be calculated as $\sigma_{S4}^2 = 2\sigma_\phi^2$, and the covariance is $\mathrm{cov}_{S4}(x,y) = \sigma_\phi^2$. The encoding directions of the balanced 4-point method can be determined by the four circumradii of a regular tetrahedron. The noise variance of the decoded phase image in each direction is $\sigma_{B4}^2 = 3\sigma_\phi^2/4$, which is only 37.5% of the noise variance of the simple 4-point method, and its noise is also independent in each direction.

Methods. All studies were performed on a 1.5T MRI system (Avanto, Siemens Medical Solutions, Germany). An ECG-gated spiral sequence (7) was modified to perform either simple or balanced multi-point displacement encoding, as well as phase cycling for artifact suppression (8,9). DENSE images were acquired on a stationary water phantom to make noise variance measurements. The imaging parameters include pixel size = 2.2 × 2.2 mm^2, slice thickness = 8 mm, flip angle = 10°, TR = 18 ms, TE = 1.9 ms, number of interleaves = 10, and cardiac phases = 16. Both encoding methods used displacement encoding frequency k_e = 0.1 cycles/mm. Images of 4 healthy volunteers were also acquired to evaluate balanced encoding *in vivo*. All volunteers were scanned in accordance with protocols approved by our institutional review board and with informed consent. The *in vivo* data acquisition used encoding frequency k_e = 0.06 cycles/mm to reduce phase wrapping.

Results. Noise variance results for the stationary phantom are shown in Fig. 1, where the average noise variance ratio of the balanced method to the simple method is 37.2% (Fig. 1(A)) and 40.6% (Fig. 1(B)) through the cardiac cycle, for the 3-point and 4-point cases, respectively. Example Lagrangian displacement and strain maps of one volunteer at end systole using the balanced 3-point method are shown in Fig. 2(A) and (B), respectively.

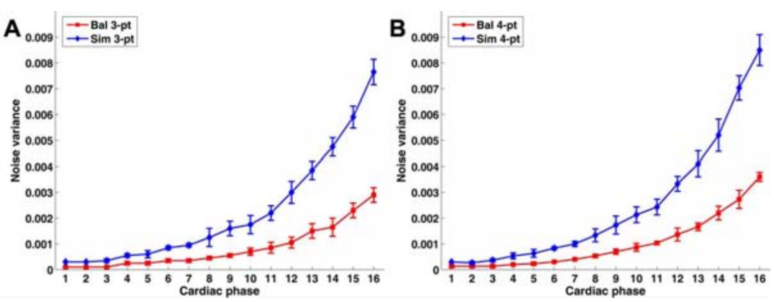

Fig. 1. Noise variance results for all available directions on the stationary phantom. (A) 3-point method for 2D encoding. (B) 4-point method for 3D encoding.

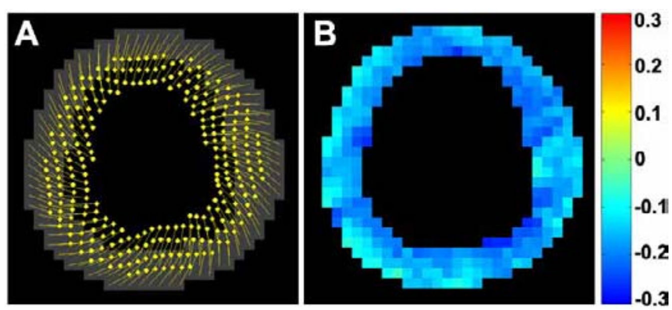

Fig. 2. Example Lagrangian (A) displacement and (B) circumferential strain (Ecc) maps using balanced 3-point displacement-encoding method.

Conclusions. The advantages of the balanced multi-point method are (a) reduced noise variance for a given value of k_e, and (b) direction independence. The disadvantage of the balanced multi-point method is more phase wrapping. Whereas in velocity-encoded PC the amount of velocity encoding could, essentially without penalty, be adjusted to provide similar phase SNR and wrapping for the simple and balanced methods, this is not the case in DENSE. In DENSE, because signal loss due to intravoxel dephasing increases with increasing k_e (4,5), there is an inherent advantage in decreasing the noise variance for a given value of k_e. The direction independence property of the balanced method should lead to a more even distribution of error throughout scans where there is heart rate and respiratory variability.

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. Pelc et al. JMRI 1991;1:405-413.
4. Epstein et al. MRM 2004;52:774-781.
5. Spottiswoode et al. IEEE-TMI; in press.
6. Conturo et al. MRM 1990 ;15:420-437.
7. Meyer. Spiral Echo-Planar Imaging . In: Echo-Planar Imaging: Theory, Technique, and Application, eds. 1998.
8. Fischer et al. MRM 1993;30(2):191-200.
9. Callot et al. MRM 2003 ;50:531-540.