Balanced Multi-point Displacement Encoding for DENSE MRI: Theoretical and Experimental Results

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Introduction. Various displacement encoding with stimulated echoes (DENSE) sequences (1,2) have employed encoding strategies that are analogous to the simple multi-point methods of velocity-encoded phase contrast (PC) MRI. A balanced four-point encoding strategy with improved noise variance and symmetry has been previously described for 3D PC (but not for 2D PC) (3). The purposes of this study were to extend the previous investigations (3,4) to a general balanced multi-point strategy for n-dimensional displacement encoding, and to demonstrate its improved noise variance and symmetry.

Theory. In the simple encoding methods, one scan is performed to provide the background phase reference, and other scans encode for displacement in the *x*, *y*, and/or *z* directions. In the balanced encoding methods, the directions of the encoding vectors are evenly distributed in space, and the encoding strength is given by the vertex coordinates of the encoding vectors. For 1D (two-point) encoding, the two scans are performed with displacement encoding of opposite polarities along one direction (Eq. 1), where ϕ_i is the phase of the DENSE image of the *i*th scan, k_e is the spatial frequency imparted to the transverse magnetization by the displacement encoding gradients, Δx, Δy and Δz are the displacements in the *x*, *y* and *z* directions, respectively, and $\Delta\theta_b$ is the background phase. For 2D (three-point) encoding, the encoding directions must be along the three circumradii of an equilateral triangle with center located at the origin (Eq. 2). To normalize the encoding weighting, the composite displacement-encoding vector is set as a unit vector. For 3D (four-point) encoding, the encoding directions are determined by the four circumradii of a regular tetrahedron (Eq. 3). Assuming the phase noise is equal and uncorrelated in each acquisition, the ratio of the phase noise variance measured by balanced methods to that measured by simple methods can be shown to be 25%, 33.3% and 37.5% for 1D, 2D and 3D encoding cases, respectively. The phase noise covariance between any two directions with balanced methods is always zero, while that with simple methods is always the same value as the phase noise variance in each single acquisition.

$$\begin{bmatrix}\phi_1\\ \phi_2\end{bmatrix}=\begin{bmatrix}1 & 1\\ -1 & 1\end{bmatrix}\begin{bmatrix}k_e\Delta x\\ \Delta\theta_b\end{bmatrix}$$

Eq. 1

$$\begin{bmatrix}\phi_1\\ \phi_2\\ \phi_3\end{bmatrix}=\begin{bmatrix}1 & 0 & 1\\ -1/2 & \sqrt{3}/2 & 1\\ -1/2 & -\sqrt{3}/2 & 1\end{bmatrix}\begin{bmatrix}k_e\Delta x\\ k_e\Delta y\\ \Delta\theta_b\end{bmatrix}$$

Eq. 2

$$\begin{bmatrix}\phi_1\\ \phi_2\\ \phi_3\\ \phi_4\end{bmatrix}=\begin{bmatrix}-\sqrt{3}/3 & -\sqrt{3}/3 & -\sqrt{3}/3 & 1\\ \sqrt{3}/3 & \sqrt{3}/3 & -\sqrt{3}/3 & 1\\ \sqrt{3}/3 & -\sqrt{3}/3 & \sqrt{3}/3 & 1\\ -\sqrt{3}/3 & \sqrt{3}/3 & \sqrt{3}/3 & 1\end{bmatrix}\begin{bmatrix}k_e\Delta x\\ k_e\Delta y\\ k_e\Delta z\\ \Delta\theta_b\end{bmatrix}$$

Eq. 3

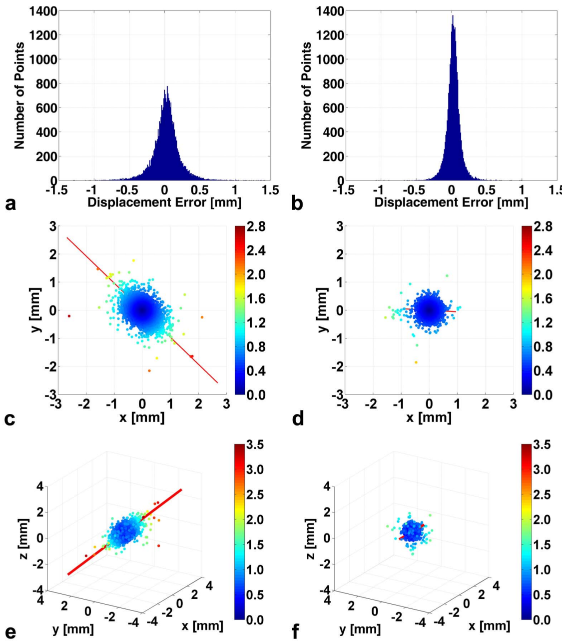

Fig. 1 Measured displacement error histograms (a,b) and scatter plots (c-f) for simple (left column) and balanced (right column) multi-point encoding methods. Top row: 1D encoding. Middle row: 2D encoding. Bottom row: 3D encoding. The color of the points in (c-f) represents the magnitude of the displacement error vector. The red straight lines in (c-f) indicate the strength and direction of direction biases of encoding strategies.

Methods. All studies were performed on a 1.5T MRI system (Avanto, Siemens Medical Solutions, Germany). An ECG-gated spiral cine DENSE pulse sequence (5) was modified to perform either simple or balanced displacement encoding, as well as phase cycling (6) for artifact suppression. A stationary water phantom was scanned to evaluate the phase noise variance. The imaging parameters included pixel size = 2.5 $\times$ 2.5 mm^2, slice thickness = 2.5 mm, flip angle = 20°, TR = 18 ms, TE = 1.8 ms, number of interleaves = 6, temporal resolution = 36 ms, and frames = 16. Both encoding methods used displacement encoding frequency k_e = 0.1 cycles/mm. Through-plane dephasing with the frequency of k_d = 0.08 cycles/mm was used for improved artifact suppression for the cases of 1D and 2D encoding (7). Phase noise variance and covariance between any two directions were calculated using the displacement-encoded phase. The direction bias of displacement error vectors in 2D and 3D cases, which has a value of 0 for the perfectly isotropic case and a value of 1 when a single direction bias exists, was quantified using principal component analysis. Both methods were also performed for 2D imaging on a healthy volunteer in accordance with protocols approved by our institutional review board. Different imaging parameters included pixel size = 2.4 $\times$ 2.4 mm^2, slice thickness = 5 mm, TR = 15 ms, TE = 1.2 ms, temporal resolution = 30 ms, and frames = 24. Both methods used displacement encoding frequency k_e = 0.06 cycles/mm. Two-point phase cycling with through-plane dephasing was used during breath-holding for artifact suppression (7). Displacement and strain analysis of the cine DENSE data were performed offline using methods described previously (8).

Results. In agreement with theory, using balanced methods the phase noise variance measured on the phantom decreased by 73.7%, 65.6%, and 61.9% compared to simple methods for 1D, 2D and 3D encoding, respectively. Similarly, phase noise covariances decreased by 99.2% and 99.3% for balanced 2D and 3D encoding. Histograms and scatter plots of the displacement error vectors of both balanced and simple methods are shown in Fig. 1. Smaller displacement errors were achieved by balanced methods. Moreover, for three- and four-point methods, direction biases were 0.53 and 0.71 using simple methods, respectively, while balanced methods displayed greatly reduced direction biases of 0.09 and 0.07, respectively. In Fig. 2, reduced noise is observed in the phase and strain images of the volunteer for the balanced method compared to the simple method.

Conclusion. Balanced multi-point encoding methods provide reduced phase noise variance for a given displacement encoding frequency, and eliminate the direction bias in phase noise. The algorithms for the balanced methods in this study can be applied generally to encode in n dimensions for DENSE acquisitions, and can also be applied to velocity-encoded PC imaging.

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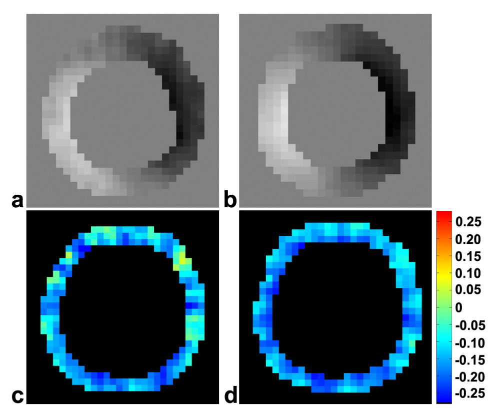

Fig. 2 Example end-systolic short-axis DENSE phase images (a,b) and circumferential strain (c,d) maps of the LV of a healthy volunteer for both simple (a, c) and balanced (b, d) three-point displacement-encoding. Reduced phase and strain noise is observed in (b,d), respectively.