Combining 2D DENSE and SENC to Calculate the 3D Strain Tensor

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Introduction. Two-dimensional cine DENSE (Displacement encoding with stimulated echoes) [1] and SENC (Strain Encoding) [2] are quantitative techniques for measuring in-plane and through-plane myocardial strain, respectively. The purpose of the present study was to develop methods for measuring the complete 3D strain tensor in individual short-axis slices by combining DENSE and SENC data.

Methods. Cine DENSE and SENC sequences that use echo-planar imaging for rapid data acquisition were implemented on a Siemens 1.5T Avanto MR scanner. For cine DENSE, phase reference data and data encoded for displacement in each of two orthogonal in-plane directions were acquired in two breathholds. For SENC, a phase reference image as well as images with two different k_z tuning frequencies were acquired in a single breathhold. Both sequences used a matrix size of 128 x 96, a 15° flip angle, TR = 22ms, ETL = 9, segments = 18 and phases = 18. Differences between imaging parameters for the two sequences were 1) readout FOV = 360mm for cine DENSE and 480mm for SENC, and 2) slice thickness = 8mm for cine DENSE and 16mm for cine SENC. For SENC the k_z encoding frequency was 0.15 mm^{-1} and the tuning frequencies were 0.15 mm^{-1} and 0.185 mm^{-1}.

$$invF = \begin{bmatrix} \frac{\partial x_1}{\partial X_1} & \frac{\partial x_1}{\partial X_2} & \frac{\partial x_1}{\partial X_3} \\ \frac{\partial x_2}{\partial X_1} & \frac{\partial x_2}{\partial X_2} & \frac{\partial x_2}{\partial X_3} \\ \frac{\partial x_3}{\partial X_1} & \frac{\partial x_3}{\partial X_2} & \frac{\partial x_3}{\partial X_3} \end{bmatrix}$$

Figure 1: The inverse deformation gradient

The 3D Lagrangian strain tensor was calculated using $E = \frac{1}{2}(F^T F - I)$ where F is the deformation gradient and I is the identity matrix. In order to fully describe F, two adjacent cine DENSE planes were imaged with 2D in-plane displacement encoding, covering 16 mm longitudinally. This 16mm slice was then imaged using cine SENC. The components of the inverse F ($invF$) are depicted in figure 1. The $(invF)_{1,1}$, $(invF)_{2,1}$, $(invF)_{1,2}$, and $(invF)_{2,2}$ components were calculated using the two adjacent 2D cine DENSE planes. $(invF)_{1,3}$ and $(invF)_{2,3}$ were derived from the difference between the 2D DENSE displacements of two vertically adjacent voxels in the two imaging planes. The $(invF)_{3,1}$ and $(invF)_{3,2}$ components were determined from the spatial gradient of phase of the cine SENC images, which is the tilt of the tag planes out of the imaging plane combined with the, $(invF)_{1,1}$ $(invF)_{2,1}$ or $(invF)_{1,2}$, $(invF)_{2,2}$ components. The final $(invF)_{3,3}$ component was calculated using the change in tag frequency [2] combined again with the $(invF)_{1,3}$ $(invF)_{2,3}$ components and the SENC spatial gradient of phase. Principal strains were calculated using eigenvector decomposition. For acquiring an additional adjacent plane of strain data, one extra 2D DENSE and one SENC acquisition would be required. This technique was evaluated by acquiring mid-ventricular short-axis images in four healthy volunteers after obtaining written consent. All imaging was performed in accordance with protocols approved by our institution's investigational review board.

Results. In all volunteers, E_1 was positive, oriented in the radial direction, essentially lay within the short axis imaging plane, and had maximum magnitudes of approximately 30% strain. E_2 was predominantly oriented longitudinally with a circumferential component at end systole and minimum values of approximately –15% strain. E_3 was oriented circumferentially with a longitudinal component and had minimum values of approximately –25% strain. The E_3 vector is oriented as part of a clockwise spiral from apex to base, viewed from the base. The vectors of the principal strains at end systole for one volunteer are shown in figure 2.

Conclusions. The magnitudes and directions of the principal strains at end systole agree closely with those reported by Moore at al [3], except that E_2 and E_3 are more closely aligned to the through-plane and circumferential directions, respectively. The apparent spiral formed by E_3 is also in agreement with Moore [3]. Thus this technique is able to calculate the 3D strain tensor of a single mid-ventricular slice by using SENC to minimize the error introduced in the through-plane components by multiple breath-holds.

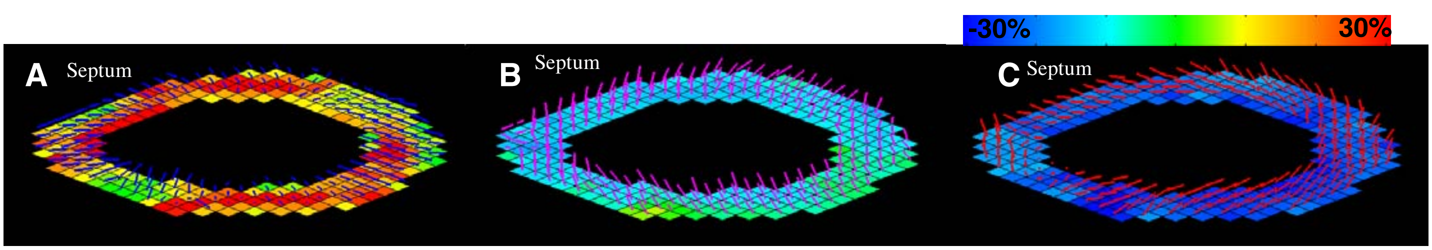

Figure 2: The magnitudes and directions at end systole of (A) first principal, (B) second principal, and (C) third principal strains.

1. Kim et al. Radiology 2004; 230:862-871.
2. Osman et al. Magnetic Resonance in Medicine 2001; 46:324-334
3. Moore et al. Radiology 2000; 214:453-466.

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