A Hybrid Method for Automatic Reconstruction of 3D Tissue Displacement Fields from MRI

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Introduction: Myocardial tissue displacement measurement is essential for biomechanical modeling and clinical diagnosis, as exemplified in the left ventricle where infarct zones can be delineated via strain information [1]. However, these measurements are often limited by low spatial resolution and subjective, laborious post-analysis, making automated high-resolution 3D tissue displacement assessment techniques highly desirable. Because of its exceptional soft tissue sensitivity, magnetic resonance imaging (MRI) has been used to track tissue motion by intensity modulation techniques, like tagging [2], and displacement encoding with stimulated echoes (DENSE) [3], or by image registration, as in Hyperelastic Warping [4]. DENSE and Hyperelastic Warping provide pixel-level resolution, but each has its practical limitations. DENSE encodes displacement in the phase angle of the complex MRI signal, which can “wrap around” when its value exceeds 360^0. Although phase “unwrapping” can be and has been performed [5], reliable results often need assumptions or subjective user-input reference values. Alternatively, Hyperelastic Warping estimates displacement from before- and after-deformation images. Without accurate modeling parameters, this method is relatively inaccurate in areas away from an object’s border or without texture information. Here, we propose a method to combine DENSE and Hyperelastic Warping to obtain reliable displacement fields automatically, and without the need of accurate modeling parameters or assumptions about the motion.

Materials and Methods:
Theory. The displacement vector field obtained from Hyperelastic Warping, $\vec{v}_w(\vec{r})$, has highest confidence when the displacement is parallel to the local image intensity gradient $\nabla S(\vec{r})$. In contrast, properly sampled DENSE fields $\vec{v}_d(\vec{r})$ can be accurate except for possible reference offset $\vec{v}_{ref}$. Combined, the projections of $\vec{v}_w(\vec{r})$ and $\vec{v}_d(\vec{r})$ along $\nabla S(\vec{r})$ can be used as the constraining criterion to determine the DENSE and the true displacement field $\vec{v}(\vec{r})$ according to the following equation,

$$\int_B \vec{v}_w(\vec{r}) \cdot \nabla S(\vec{r})\, dB = \int_B (\vec{v}_d(\vec{r}) - \vec{v}_{ref}) \cdot \nabla S(\vec{r}) dB = \int_B \vec{v}(\vec{r}) \cdot \nabla S(\vec{r})\, dB.$$

Verification. This method was tested on a numerical phantom where simulated images for registration and wrapped DENSE images were generated from a known, inhomogeneous 3D “gold standard” displacement field. The displacement measurements obtained from the images were compared to the gold standard.
In Vivo Imaging. Cardiac DENSE-MRI (8 slices, TR/TE = 15.0/2.0 ms , 3 frames, FOV 40x40 mm, 96x96 pixel) was performed on an isoflurane-anesthetized rat using a Bruker Biospec 7T scanner. DENSE magnitude images were used for Hyperelastic Warping in a voxel-per-element mesh and arbitrary modeling parameters.

Results and Discussion: The method was able to reconstruct the gold standard consistently, despite some variations in registration and reconstruction parameters. Representative displacement fields from diastole-to-systole motion are shown in Fig 1. Without reference adjustment, the DENSE result is not coherent with the deformation of the heart (Fig 1, b). The combined approach result (Fig 1. d) is coherent with the displacement of the heart, a slight rotation is also observed, which does not appear in the Hyperelastic Warping solution (Fig 1. c).

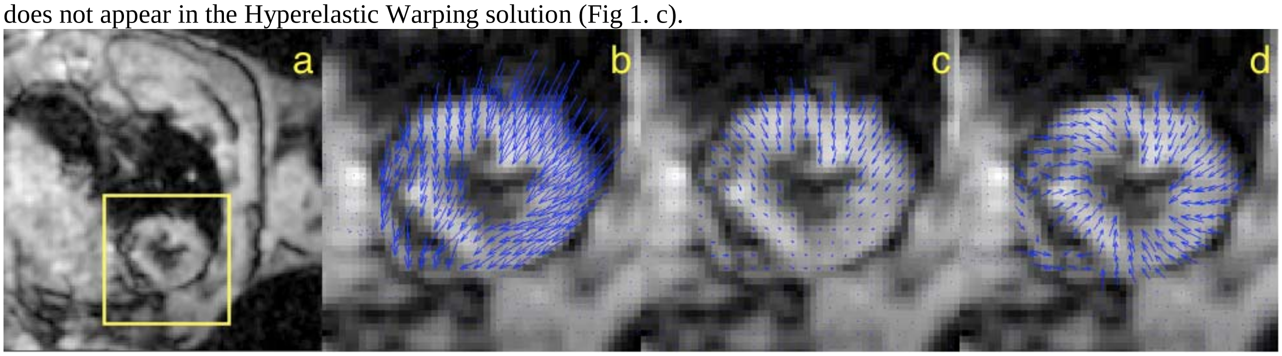

Figure 1. a) Axial slice showing the heart in the box, b) DENSE without reference correction, c) Hyperelastic Warping displacement field, d) Combined approach—note physiologically accurate displacements obtained automatically.

Conclusions: Combining Hyperelastic Warping and DENSE to measure tissue displacement uses image registration to compensate for bulk displacements missed by DENSE alone because of phase wrapping. The combined approach is a relatively simple and robust way to produce pixel-level 3D displacement vector fields.

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