In-Vivo 3-D Left Ventricular Strain Estimation from a 3-D Tag Sequence Using Optical Flow Method

C. Xu[1], L. Dougherty[2], G. Isaac[2], A. Blom[1], J. H. Gorman[1], R. C. Gorman[1], and J. J. Pilla[1,2]

[1]Harrison Department of Surgical Research, University of Pennsylvania, Glennolden, PA, United States, [2]Department of Radiology, University of Pennsylvania, Philadelphia, PA, United States

INTRODUCTION Numerous methods have been proposed to reconstruct cardiac motion from tagged MR images for the purpose of quantification of cardiac mechanics and dynamics. The majority of analysis has been limited to 2-D, which is not sufficient to precisely capture the complex motion associated with normal and diseased hearts. Existing 3-D analysis methods consist of pre-defined deformable models and sparse material points tracking, which both use multiple orthogonal tag image acquisition sets and suffer from long acquisition time and less than optimal spatial resolution. This study presents a method of obtaining and analyzing 3-D tagged images to generate direct 3-D strain with less post-processing time and higher spatial resolution in human subjects.

METHODS In order to rapidly acquire a 3-D tagged image set without multiple orthogonal scans, a pulse sequence was developed that applied the SPAMM tag prep pulse in three distinct planes in one acquisition. Two orthogonal sets of tags were oriented through-plane, while the third tag plane was applied at a defined angle relative to the through-plane tags. The normal of the in-plane tag orientation relative to the through-plane tags was optimized in a previous study using a simulation model and was set at 35, 66 and 66 degrees. Displacement of each pixel was tracked with sub-pixel resolution using a 3-D Optical Flow Method (3-D OFM) where the parameters and filtering were optimized in the previous simulation. Lagrangian strain tensor was derived from flow fields, and maximum and minimum principal strains (ε_1 and ε_3) were computed. Regional and local cardiac functions were quantified by first identifying the mid-point of anterior RV insertion on each slice. The LV myocardium was then divided into four circumferentially equal regions: anterior, septal, lateral and posterior; and three longitudinally equal segments: apical, mid-ventricular and basal. Displacement and deformation were averaged over each segment to measure regional cardiac mechanics. To demonstrate the method a 3-D tag data set was acquired from a healthy normal volunteer using a 2-D fast gradient echo (FGRE) sequence with the optimized 3-D tag preparatory pulse on a 1.5 T Siemens Sonata scanner (Siemens Medical Solutions, Malvern, PA, USA). Breath hold and ECG gating were performed to minimize respiratory and cardiac motion. Anterior and posterior phased array flex coils were placed on the subject and imaging was performed with the following parameters: TR/TE/FA=3.8ms/2.65ms/15^0, Averages=2, views per segment= 6, slice thickness= 4 mm, raw data matrix 256x96, interpolated to 256x192, rectangular field of view 260mm x 195mm, 16 slices.

RESULTS Vector plots of in plane flow fields derived by 3-D OFM reveal complex and detailed myocardial displacement patterns (Figure. 1, A and B). Significantly smaller longitudinal displacement was observed in the apical region (Figure. 1, E and F), while the longitudinal strain was greatest between the mid-ventricular and apical sections. Color-coded vector plots of integrated systolic flow fields (Figure. 2) indicate an increase in displacement from apex to base and from epicardium to endocardium. At each location radial wall thickening (ε_1) was smallest at the septum and greatest in the free wall (anterior, posterior and lateral regions). Representing maximum shortening, ε_3 was consistently aligned with the circumferential-longitudinal direction, and was greatest in the mid-ventricular section and significantly smaller in the basal region (Table 1).

CONCLUSION This study has demonstrated an innovative method to estimate displacement and deformation in the LV wall of a human heart by combining a 3-D tag sequence, 3-D OFM and finite element analysis. Regional strains generated from this method are in agreement with results from other research groups [1, 2] but required significantly shorter acquisition and analysis time. In addition, we achieved greater in-plane and through-plane spatial resolution. The method presented in this paper has the potential to generate high-resolution LV regional 3-D strain, which could lead to improved characterization of the mechanics in normal and diseased hearts.

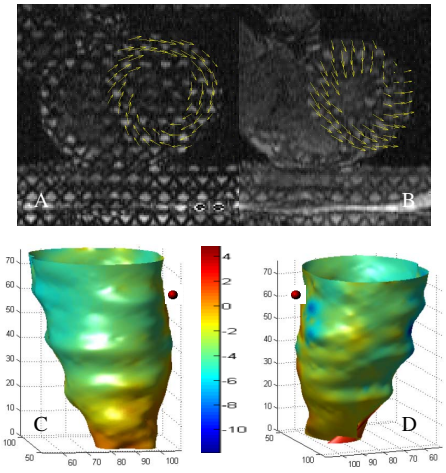

FIGURE 1. In-plane flow fields of a mid-ventricular short axis image at early-systole (A) and end-systole (B). (C) and (D) show two views of the reconstructed LV mid-wall surface color-coded by apex-base displacement (mm). Position of RV was marked as reference.

TABLE 1. Principal strains (ε_1 and ε_3) during systole evaluated from a healthy volunteer, measured as mean +/- SD

		ε1		ε3	
Apex	Septal	0.1	0.1	-0.2	0.1
	Posterior	0.2	0.1	-0.2	0.1
	Lateral	0.2	0.1	-0.2	0.1
	Anterior	0.2	0.1	-0.2	0.1
Mid	Septal	0.1	0.1	-0.3	0.1
	Posterior	0.3	0.2	-0.3	0.1
	Lateral	0.3	0.1	-0.3	0.1
	Anterior	0.2	0.1	-0.3	0.1
Base	Septal	0.1	0.0	-0.1	0.1
	Posterior	0.3	0.2	-0.1	0.0
	Lateral	0.3	0.1	-0.1	0.1
	Anterior	0.2	0.1	-0.2	0.1

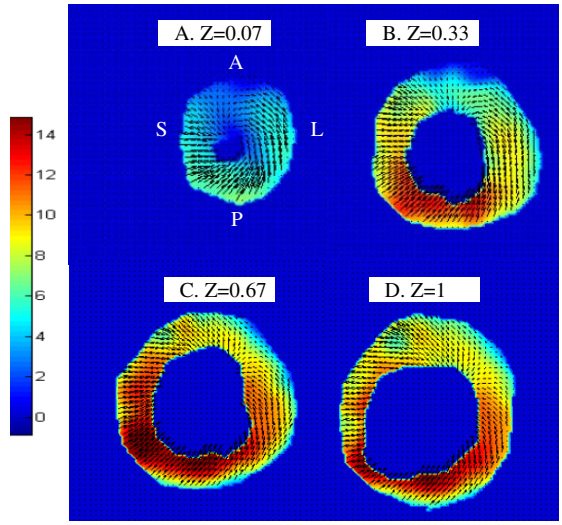

FIGURE 2. (A) to (D): integrated systolic displacement (mm) at four representative normalized short axis planes.

1. Moore, C.C., et al., *Three-dimensional systolic strain patterns in the normal human left ventricle: characterization with tagged MR imaging.* Radiology, 2000. **214**(2): p. 453-66.
2. Young, A.A., et al., *Three-dimensional left ventricular deformation in hypertrophic cardiomyopathy.* Circulation, 1994. **90**(2): p. 854-67.