An Effective 3-Dimensional Regional Myocardial Strain Computation Method with Displacement ENcoding with Stimulated Echoes (DENSE) in Dilated Cardiomyopathy Patients and Healthy Subjects

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Abstract. Fast Cine Displacement ENcoding with Stimulated Echoes (DENSE) is a magnetic resonance imaging (MRI) technique attributed with higher spatial resolution and rapid post-processing. Our primary goal was three-dimensional (3D) regional strains quantification using DENSE images in healthy subjects and non-ischemic, non-valvular dilated cardiomyopathy (DCM) patients, followed by validation with comparison to a standard established sequence. Cine DENSE data were acquired using an echo planar imaging (EPI) sequence. A meshfree multiquadrics radial point interpolation method (RPIM) was used for computing Lagrange strains in sixteen left ventricular segments. Validation of 3D regional strains computed with DENSE was conducted in reference to standard tagged MRI via Bland-Altman analyses. Additionally, repeatability studies in DENSE were conducted with healthy subjects and Bland-Altman analysis between repeated measures conducted to increase confidence in DENSE. Welch-Satterthwaite t-tests were used to estimate differences in DENSE generated regional strains between DCM and healthy subjects. Computed regional circumferential strain differences were 0.01 ± 0.03 (95% limits of agreement) from the DENSE-tagged MRI comparison in healthy subjects, -0.01 ± 0.05 from the DENSE-tagged MRI comparison in DCM patients, 0.0 ± 0.02 from repeatability studies and similar agreements were found in longitudinal and radial strains. Good regional strain agreements between modalities and in repeatability studies validated high resolution DENSE as a reliable modality for estimating 3D strains in cardiovascular biomechanics.

Keywords: DENSE; tagged MRI; RPIM; Lagrange strain; Bland-Altman

1 Introduction

Attributes of higher spatial resolution and fast accurate quantification of tissue displacement make cine Displacement ENcoding with Stimulated Echoes (DENSE) one of the most viable noninvasive technologies in cardiovascular magnetic resonance (1,2). The radial point interpolation method (RPIM) is a meshfree numerical simulation technique that facilitates fast multidimensional computation of Lagrange strains without requiring computationally intensive remeshing techniques otherwise used in conventional finite element applications (FEA) (3). This study investigated the accuracy of computing 3D left ventricular (LV) regional strains with a combined DENSE-RPIM framework in healthy subjects and in patients with nonischemic, nonvalvular dilated cardiomyopathy (DCM).

2 Methods

Cine DENSE data were acquired with displacement encoding applied in one through-plane and two orthogonal in-plane directions using an echo planar imaging (EPI) sequence (1). Offline segmentation of the myocardium, phase unwrapping in DENSE and tracking tag deformations in tagged MRI were accomplished with custom algorithms developed in our laboratory, with more details outlined in preceding publications (1,4). The 3D LV geometry was divided into sixteen American Heart Association (AHA) recommended segments as part of the 3D reconstruction process and the segmental strains later used for statistical comparison (1). A rapid phase unwrapping algorithm, consisting of computing and averaging phase angles of a series of Fourier transforms in an image, was applied to obtain displacement information from the phases of complex images in DENSE. Details of the quality guided spatiotemporal phase unwrapping algorithm can be found in a preceding 2D study which was extended to 3D by phase unwrapping in the longitudinal direction (1,2). A numerical simulation framework of meshfree multiquadrics RPIM consisting of both radial and polynomial basis functions were used for computing Lagrange strains in the sixteen LV regions segmented (3). Regional strains computed with DENSE were validated in reference to standard tagged MRI in both healthy subjects (n=12) and DCM patients (n=6). Additional repeatability studies in healthy subjects (n=10) were conducted to establish intraobserver reliability and increase confidence in DENSE as a modality for accurate displacement mapping. Bland-Altman analyses were conducted to observe regional strain agreements between DENSE and tagged MRI modalities and also in DENSE repeatability studies. Welch-Satterthwaite t-tests were conducted to estimate differences in DENSE generated regional strains between DCM and healthy subjects.

3 Results

Differences obtained from Bland-Altman analyses between DENSE and tagged MRI regional strains in normal subjects were 0.01 ± 0.03 in circumferential, 0.02 ± 0.07 in longitudinal and -0.01 ± 0.10 in radial strains. Differences in regional strains from the repeatability studies were 0.0 ± 0.02 in circumferential, -0.02 ± 0.04 in longitudinal and -0.02 ± 0.08 in radial directions. Differences from DENSE-tagged MRI regional strain comparisons in DCM patients were -0.01 ± 0.05 in circumferential, 0.02 ± 0.07 in longitudinal and -0.01 ± 0.04 in radial directions. Confidence intervals for strain differences between DCM patients and normal subjects, both estimated with DENSE, were -0.14 – -0.11 in circumferential, -0.10 – -0.07 in longitudinal and 0.11 – 0.15 in radial directions ($p < 0.001$).

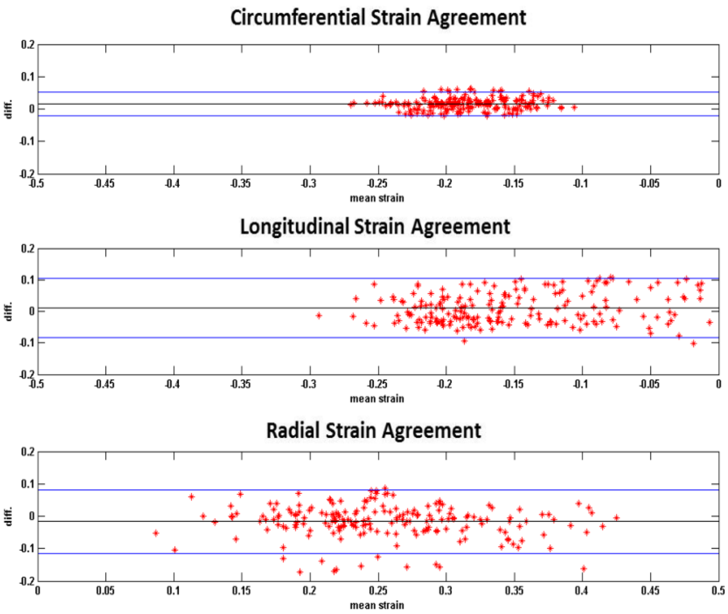

Fig. 1. Agreements in circumferential, longitudinal and radial strains between DENSE and tagged-MRI in 12 normal subjects.

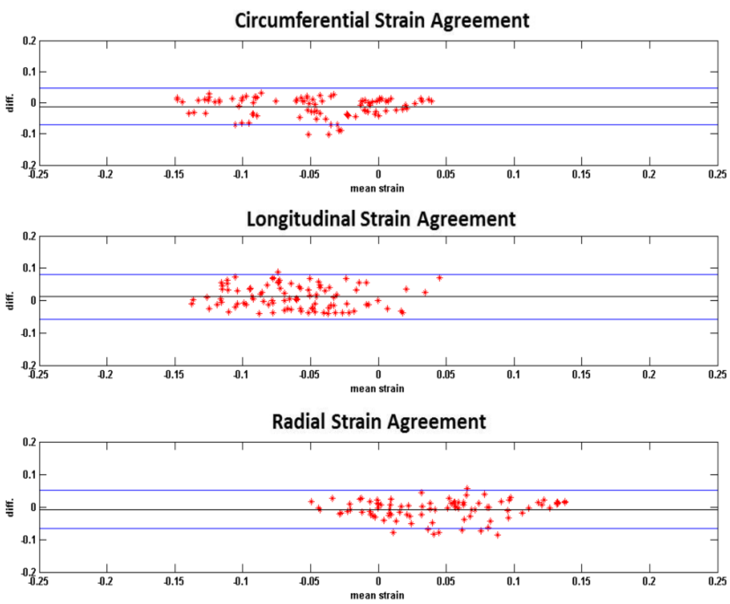

Fig. 2. Agreements in circumferential, longitudinal and radial strains between DENSE and tagged-MRI in 6 Dilated Cardiomyopathy (DCM) patients.

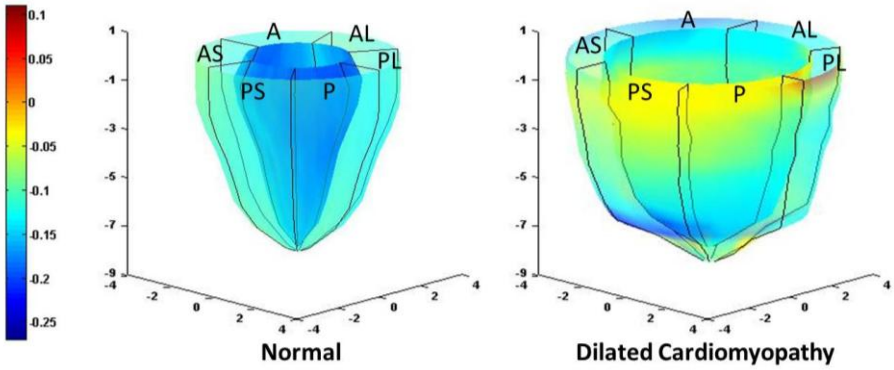

Fig. 3. Myocardial circumferential 3D strain contours in a healthy subject and a DCM patient.

Fig. 1 and 2 show the results of Bland-Altman analysis in healthy subjects and DCM patients, respectively. Fig. 3 shows 3D strain contours in circumferential strain in a normal subject and a DCM patient.

4 Conclusion

Good regional strain agreements between modalities and in repeatability studies validate high resolution DENSE as a modality that produce reliable estimates of regional strains in cardiovascular (LV) biomechanics. Confidence intervals for the differences in DCM and normal strains demonstrate the ability to quantify myocardium dysfunction with the DENSE-RPIM framework. The favorable results also imply a potential for consolidating the DENSE-RPIM framework into a significant prognostic tool for risk stratification in DCM.

5 References

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