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Heart deformation analysis for automated quantification of cardiac function and regional myocardial motion patterns: A proof of concept study in patients with cardiomyopathy and healthy subjects

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ABSTRACT

Objective: To test the performance of HDA in characterizing left ventricular (LV) function and regional myocardial motion patterns in the context of cardiomyopathy based on cine cardiovascular magnetic resonance (CMR).

Materials and methods: Following the approval of the institutional review board (IRB), standard cine images of 45 subjects, including 15 healthy volunteers, 15 patients with hypertrophic cardiomyopathy (HCM) and 15 patients with dilated cardiomyopathy (DCM) were retrospectively analyzed using HDA. The variations of LV ejection fraction (LVEF), LV mass (LVM), and regional myocardial motion indices, including radial (Drr), circumferential (Dcc) displacement, radial (Vrr) and circumferential (Vcc) velocity, radial (Err), circumferential (Ecc) and shear (Ess) strain and radial (SRr) and circumferential (SRc) strain rate, were calculated and compared among subject groups. Inter-study reproducibility of HDA-derived myocardial motion indices were tested on 15 volunteers by using intra-class correlation coefficient (ICC) and coefficient of variation (CoV).

Results: HDA identified significant differences in cardiac function and motion indices between subject groups. DCM patients had significantly lower LVEF ($33.5 \pm 9.65\%$), LVM (105.88 ± 21.93 g), peak Drr (0.29 ± 0.11 cm), Vrr-sys (2.14 ± 0.72 cm/s), Err (0.17 ± 0.08), Ecc (-0.08 ± 0.03), SRr-sys ($0.91 \pm 0.44 s^{-1}$) and SRc-sys ($-0.64 \pm 0.27 s^{-1}$) compared to the other two groups. HCM patients demonstrated increased LVM (171.69 ± 34.19) and lower peak Vcc-dia (0.78 ± 0.30 cm/s) than other subjects. Good inter-study reproducibility was found for all HDA-derived myocardial indices in healthy volunteers (ICC = 0.664–0.942, CoV = 15.1%–37.1%).

Conclusion: Without the need for operator interaction, HDA is a reproducible method for the automated characterization of global and regional LV function in the context of cardiomyopathy.

1. Introduction

Cardiovascular magnetic resonance (CMR) has become a standard tool that is able to noninvasive characterization of global and regional cardiac function for the assessment of cardiovascular disease (CVD). At the global level, left ventricular ejection fraction (LVEF) and mass (LVM) are routinely calculated based on balanced steady-state free precession (bSSFP) cine images. As a result, bSSFP acquisition has become a standard part in most clinical CMR protocols. On the other hand, in order to assess the subtle progression of CVD at the regional level, indices that present motion patterns of local myocardial areas can be acquired with various CMR techniques, including myocardial tagging, tissue phase mapping (TPM), strain-encoded (SENC) or *D*isplacement encoding with stimulated echoes (DENSE) [1–4]. Unfortunately, current CMR methods for the quantification of regional myocardial motion patterns usually require dedicated image acquisition methods, special data analysis tools, and variable processing time.

Based on deformable image registration (DIR) algorithms, heart deformation analysis (HDA) is a post-processing method for tracking myocardial motion on conventional bSSFP images [5]. Using an inverse consistent DIR algorithm to recover deformation fields (for-

Abbreviations: HDA, heart deformation analysis; CMR, cardiovascular magnetic resonance; LVEF, left ventricular ejection fraction; LVM, left ventricular mass; Drr, radial displacement; Dcc, circumferential displacement; Vrr, radial velocity; Vcc, circumferential velocity; Err, radial strain; Ecc, circumferential strain; Ess, shear strain; SRr, radial strain rate; SRc, circumferential strain rate.

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Table 1
Subject description.

	Volunteers (N = 15)	HCM patients (N = 15)	DCM patients (N = 15)
Male (%)	9 (60)	9 (60)	9 (60)
Age (years)	48.8 ± 17.5	58.0 ± 18.5	44.0 ± 17.2
Height (cm)	175 ± 8	177 ± 13	174 ± 10
Weight (kg)	73 ± 15	75 ± 12	71 ± 11

ward and backward), the HDA is able to assess variations of target deformation areas over time. From this process, global LV function and morphological changes (LVEF and LVM), as well as regional LV motion patterns (displacement, velocity, strain and strain rate), can be measured by calculating deformation fields through the cardiac cycle [6]. In addition, myocardial segmentation of the LV, including the identification of landmark anatomical structures can now be automatically performed with this technique. Comparing to existing methods for tracking myocardial motion on cine CMR, such as feature tracking (FT), HDA can further reduce the processing time and while simultaneously eliminating the intra- and inter-observer influence in quantitative analysis. Therefore, HDA represents a valuable opportunity of acquiring myocardial motion information on existing cine CMR datasets without additional scan time.

Previous studies have evaluated HDA-derived indices in describing global LV function and regional myocardial velocity in healthy volunteers using existing methods as references [7]. However, the capability and reproducibility of HDA in automated discriminating abnormal myocardial motion patterns in regionally and globally altered myocardial structure is unclear. In the present study, we compared cardiac function and myocardial motion indices derived from HDA in healthy volunteers, patients with hypertrophic cardiomyopathy (HCM), and patients with dilated cardiomyopathy (DCM). The aim of the present study was to test the performance of HDA in characterizing LV functions and regional myocardial motion patterns in the context of cardiomyopathy.

2. Materials and methods

2.1. Subject description

This study complied with HIPAA regulations. Following the approval of the institutional review board (IRB), cine bSSFP images of 45 subjects, including 15 healthy volunteers (9 men, group #1), 15 HCM patients (9 men, group #2) and 15 DCM patients (9 men, group #3) were retrospectively included for analysis (Table 1). Inclusion criteria: (1) All subject age: 18–80 years old; (2) All patients with cardiomyopathy were diagnosed according to the clinical practice guidelines published by the American Heart Association (AHA); (3) HCM was defined as patients with thickened LV wall (>15 mm) using echocardiography, without a causative cardiac or systemic disorder, such as hypertensive heart disease [8]; and (4) DCM was defined as systolic dysfunction with LVEF (<45%) accompanied with LV dilation measured with echocardiography [9]. Exclusion criteria: (1) Patients with co-existing CVD, such as myocardial infarction (MI); and (2) Volunteers with documented CVD.

2.2. CMR scans

All participants underwent CMR examinations using the same cardiac cine protocol on a 1.5 T scanner (Avanto, Siemens AG, Germany). Certified clinical radiology technologists performed all CMR scans. At four-chamber, two-chamber, and short-axis views, segmented bSSFP cine sequences were run in the cardiac imaging planes under conditions of breath-holding. Imaging parameters were as follows: TR/TE = 2.8/1.1 ms; flip angle = 65°, voxel size = 2.1 × 2.1 × 8.0 mm^3, bandwidth = 930 Hz/pixel, parallel imaging (GRAPPA technique) with reduction factor R = 2. Ten to twelve short-axis myocardial slices were set to cover the entire LV from base to apex. Each cine acquisition was acquired with retrospective ECG-gating and reconstructed into 25 cardiac time frames.

2.3. Post processing using the HDA tool

Cine CMR images, including 2-chamber, 4-chamber and a stack of short-axis images were loaded to a dedicated image processing workstation (Dell, STUDIO, SPS 435T) and analyzed with prototype software programmed in Visual C++ (TrufiStrain, Siemens Corporation, Princeton, NJ) by an experienced analyzer (K.L., reader #1, with 9 years of experience in cardiovascular imaging). Different from an existing study, the improved HDA tool automatically detected anatomical landmarks in the heart, including the mitral valve anchor points and apex point in the long-axis images, aortic valve anchor points and the right ventricle [RV] insertion/lateral points on short-axis images [7]. The myocardial borders (epicardial and endocardial) were automatically delineated using an existing DIR algorithm described before [5]. Elastic image registration was then completed to calculate frame-to-frame motion deformation fields [5]. Cardiac time frames were segmented using a shortest path algorithm and time consistency was enforced through the deformation fields [10]. Global cardiac function (LVEF and LVM) and regional myocardial motion indices, including displacement, velocity, strain and strain rate, could therefore be derived from the variant deformation fields over time. Next, the in-plane time-resolved regional myocardial motion vectors in radial and circumferential directions were generated for each myocardial segment (mapped on a standard 16-segment AHA LV model).

The reader #1 judged whether the HDA-generated contours were "reasonable" for each case. If not, the reader #1 would adjust contours manually. In order to test the inter-analysis variation, the reader #1 reloaded cine SSFP images of all subjects a week later and repeat the same automatic image analysis processing method (on a different workstation installed with the same version of the HDA tool). All 15 volunteers underwent a second cardiac cine CMR scan using the same imaging protocol 2 weeks later. The retest data was used to assess the inter-study reproducibility of the HDA tool.

2.4. Data processing and statistical analysis

All continuous variables were represented by mean ± one standard deviation (SD). The global LV parameters, including LVEF and LVM, were calculated for each subject. The variations of regional myocardial motion indices, including radial (Drr) and circumferential (Dcc) displacement, radial (Vrr) and circumferential (Vcc) velocity, radial (Err), circumferential (Ecc) and shear (Ess) strain and radial (SRr) and circumferential (SRc) strain rates, were recorded through the cardiac cycle (25 time points) and were mapped on an AHA LV model (16 segments). The difference in peak values among different subject groups was compared using independent *t*-tests. Inter-study reproducibility of HDA-derived indices was tested on 15 healthy volunteers by using intra-class correlation coefficient (ICC) and coefficient of variation (CoV). An ICC value > 0.75 or a CoV < 20% between duplicated measurements was considered as good reproducibility. Bland-Altman plots were also used to show inter-study variability of HDA-derived motion indices (peak values). Statistical analyses were two-tailed and were performed using SPSS statistical software (Version 13.0, SPSS. Inc, Chicago, IL). A p value < 0.05 was considered statistically significant.