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Research paper

Automated three-dimensional tracking of the left ventricular myocardium in time-resolved and dose-modulated cardiac CT images using deformable image registration

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ABSTRACT

Background: Assessment of myocardial deformation from time-resolved cardiac computed tomography (4D CT) would augment the already available functional information from such an examination without incurring any additional costs. A deformable image registration (DIR) based approach is proposed to allow fast and automatic myocardial tracking in clinical 4D CT images.

Methods: Left ventricular myocardial tissue displacement through a cardiac cycle was tracked using a B-spline transformation based DIR. Gradient of such displacements allowed Lagrangian strain estimation with respect to end-diastole in clinical 4D CT data from ten subjects with suspected coronary artery disease. Dice similarity coefficient (DSC), point-to-curve error (PTC), and tracking error were used to assess the tracking accuracy. Wilcoxon signed rank test provided significance of tracking errors. Topology preservation was verified using Jacobian of the deformation. Reliability of estimated strains and torsion (normalized twist angle) was tested in subjects with normal function by comparing them with normal strain in the literature.

Results: Comparison with manual tracking showed high accuracy (DSC: 0.99±0.05; PTC: 0.56mm±0.47 mm) and resulted in $determinant(Jacobian) > 0$ for all subjects, indicating preservation of topology. Average radial (0.13 mm), angular (0.64) and longitudinal (0.10 mm) tracking errors for the entire cohort were not significant ($p > 0.9$). For patients with normal function, average strain [circumferential, radial, longitudinal] and peak torsion estimates were: [-23.5%, 31.1%, −17.2%] and 7.22°, respectively. These estimates were in conformity with the reported normal ranges in the existing literature.

Conclusions: Accurate wall deformation tracking and subsequent strain estimation are feasible with the proposed method using only routine time-resolved 3D cardiac CT.

1. Introduction

Quantification of myocardial deformation from time-resolved three-dimensional cardiac CT (or 4D CT) would extend the amount of functional information that is currently obtained from such an examination. 4D CT has several advantages over other imaging techniques including a high spatial resolution, short scan time and, often, fewer contra-indications. Obtaining multiple functional parameters from these data would extend the usability of 4D CT further. Myocardial strain, that provides an intuitive and orientation invariant estimate of wall deformations, can be computed from 4D CT without incurring any additional acquisition cost.[1–3] Especially, in patients with known or suspected coronary artery disease (CAD), myocardial deformation assessment would be an excellent complement to the detection of coronary artery stenosis.

Strain is typically obtained after tracking the myocardium over an entire cardiac cycle. Unfortunately, 4D CT images often have low contrast in the myocardial wall that makes its tracking extremely challenging in a large part of the cardiac cycle. Few methods exist to perform this tracking. A multi-channel Diffeomorphic Demons based nonlinear spatiotemporal framework was used in Peyrat et al.[4] to obtain trajectories of physical points in both patient and synthetic data. In

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Table 1
Patient characteristics.

	All subjects (N = 10)		Female (N = 3)		Male (N = 7)	
	mean ± std. dev.	range	mean ± std. dev.	range	mean ± std. dev.	range
Age [years]	61.0 ± 12.4	36.0–74.0	67.0 ± 5.6	62.0–73.0	58.4 ± 14.0	36.0–74.0
Height [cm]	173.8 ± 6.7	162.5–187.0	168.5 ± 7.6	162.5–177.0	176.1 ± 5.2	171.0–187.0
Weight [kg]	89.6 ± 21.9	61.7–130.0	70.6 ± 9.2	61.7–80.0	97.7 ± 20.8	72.0–130.0
Body mass index (BMI)	29.4 ± 5.7	22.4–37.3	24.8 ± 2.1	22.4–26.5	31.4 ± 5.7	22.7–37.3
Heart rate [bpm]	64.0 ± 9.1	48.0–77.0	55.3 ± 6.4	48.0–60.0	67.7 ± 7.6	60.0–77.0
Systolic blood pressure [mmHg]	144.5 ± 13.5	117.0–170.0	142.0 ± 3.6	139.0–146.0	145.6 ± 16.3	117.0–170.0
Diastolic blood pressure [mmHg]	78.6 ± 13.7	44.0–95.0	85.3 ± 3.2	83.0–89.0	75.7 ± 15.7	44.0–95.0
Acquisition dates	February 2016–November 2016					

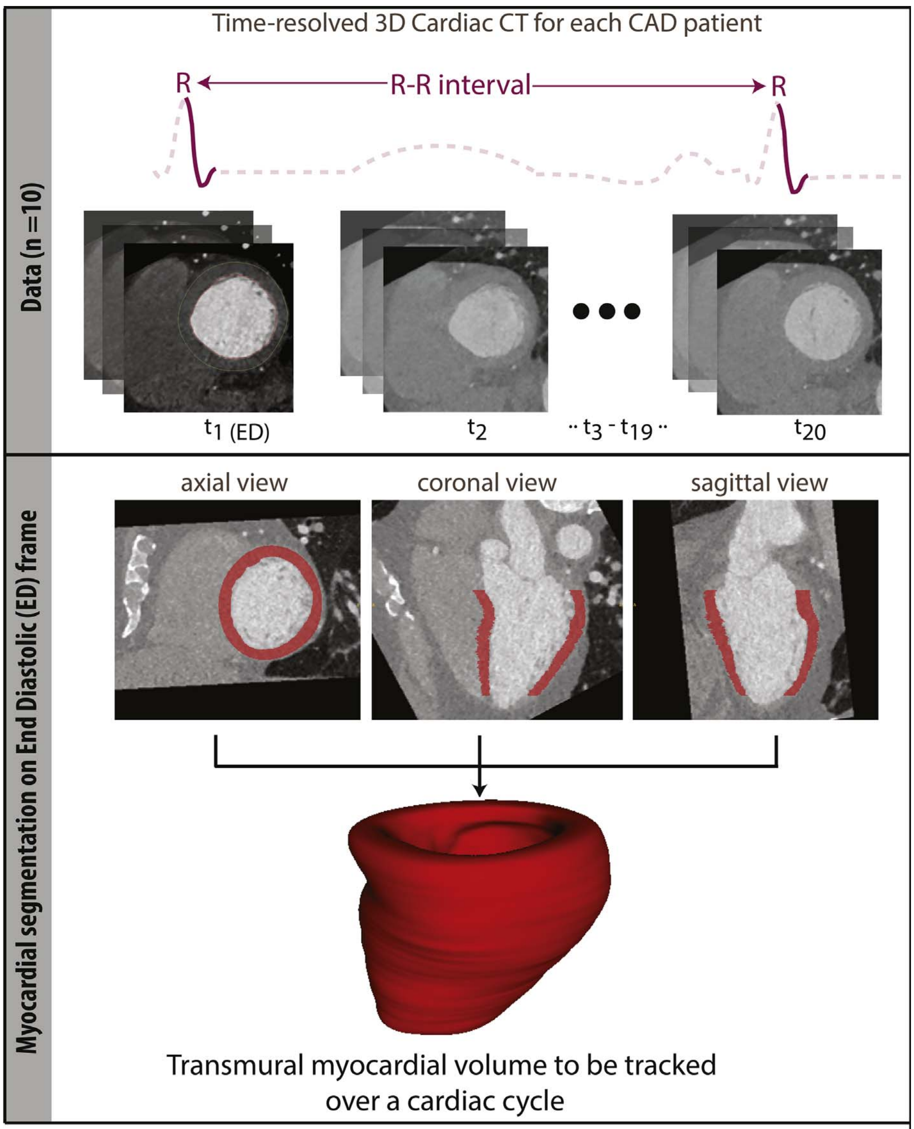

Fig. 1. Overview of the materials and segmentation method. The top row shows a typical dataset from one patient comprising 3D images from multiple phases of a cardiac cycle between two R peaks of an ECG signal. The second row illustrates how the left-ventricular myocardial volume was obtained for an end-diastolic (ED) volume.

another image registration based approach,[5,6] enforced displacements from B-spline deformable model served as boundary conditions to a biomechanical model in data from ten canines. Biomechanical modeling was also used,[1] wherein a left ventricular mesh model enabled the wall deformation tracking in different phases of a cardiac cycle.[1] In a different approach,[2] three-dimensional (3D) motion tracking was performed by constraining intensity constancy, myocardial volume changes and motion smoothness assumptions. While these studies have shown promising results, they are limited by high accuracy errors > 2.9 mm[2] or long processing time of up to 900 minutes[4] or evaluation in only synthetic and canine data,[4,5] which hampers their advancement to clinical use.

The purpose of this study was to test the clinical feasibility of a fast, accurate and automatic deformable image registration based myocardial tracking in routine 4D CT examinations and to show its potential for reliable strain estimations.