Medical Image Analysis 17 (2013) 133–146

Contents lists available at SciVerse ScienceDirect

Medical Image Analysis

journal homepage: www.elsevier.com/locate/media

The estimation of patient-specific cardiac diastolic functions from clinical measurements

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ARTICLE INFO

Article history:
Received 26 September 2011
Received in revised form 26 July 2012
Accepted 14 August 2012
Available online 16 October 2012

Keywords:
Constitutive material parameter estimation
Left ventricular (LV) mechanics
Diastolic heart failure

ABSTRACT

An unresolved issue in patients with diastolic dysfunction is that the estimation of myocardial stiffness cannot be decoupled from diastolic residual active tension (AT) because of the impaired ventricular relaxation during diastole. To address this problem, this paper presents a method for estimating diastolic mechanical parameters of the left ventricle (LV) from cine and tagged MRI measurements and LV cavity pressure recordings, separating the passive myocardial constitutive properties and diastolic residual AT. Dynamic C_1-continuous meshes are automatically built from the anatomy and deformation captured from dynamic MRI sequences. Diastolic deformation is simulated using a mechanical model that combines passive and active material properties. The problem of non-uniqueness of constitutive parameter estimation using the well known Guccione law is characterized by reformulation of this law. Using this reformulated form, and by constraining the constitutive parameters to be constant across time points during diastole, we separate the effects of passive constitutive properties and the residual AT during diastolic relaxation. Finally, the method is applied to two clinical cases and one control, demonstrating that increased residual AT during diastole provides a potential novel index for delineating healthy and pathological cases.

1. Introduction

The quantification of diastolic dysfunction is vital for the diagnosis and assessment of heart disease, enabling improved selection and treatment of individuals with pathological myocardial mechanics for further therapy (Nagel and Schuster, 2010). Patient-specific cardiac models, parameterized from clinical measurements on an individual basis, provide a powerful approach for this purpose (Smith et al., 2011). Accordingly, model-based parameter estimation from clinical measurements of cardiac function has been an active research area.

Parameters in organ-level cardiac mechanical models can be broadly classified as passive and active. Typically within computational models, passive constitutive parameters have been used to characterize the diastolic function, and with the addition of active contraction models simulate systole (Nash and Hunter, 2000; Nordsletten et al., 2011). Various frameworks and methods have been proposed to estimate these parameters (Sermesant et al., 2006, 2012; Chabiniok et al., 2011; Delingette et al., 2012; Moireau and Chapelle, 2011; Wang et al., 2009, 2010). In Sermesant et al. (2006), a variational data assimilation method was developed to estimate the contractility parameters of an electromechanical model from clinical cine MRI. Focusing on passive parameters, Wang et al. (2009) have described a workflow to estimate the Guccione constitutive parameters using high-resolution MRI data acquired from a canine heart. An approach which these authors further extended in Wang et al. (2010) to estimate the active tension (AT) during the isovolumetric contraction, systole and isovolumetric relaxation using the constitutive parameters pre-estimated during diastole.

However, an unsolved problem in patients with diastolic dysfunction is that the estimation of myocardial stiffness cannot be decoupled from impaired ventricular relaxation (one of the lusitropic abnormalities commonly present in heart failure, Katz, 2010). For this reason, the development of methods which can robustly estimate both the stiffness and residual AT during diastole

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http://dx.doi.org/10.1016/j.media.2012.08.001

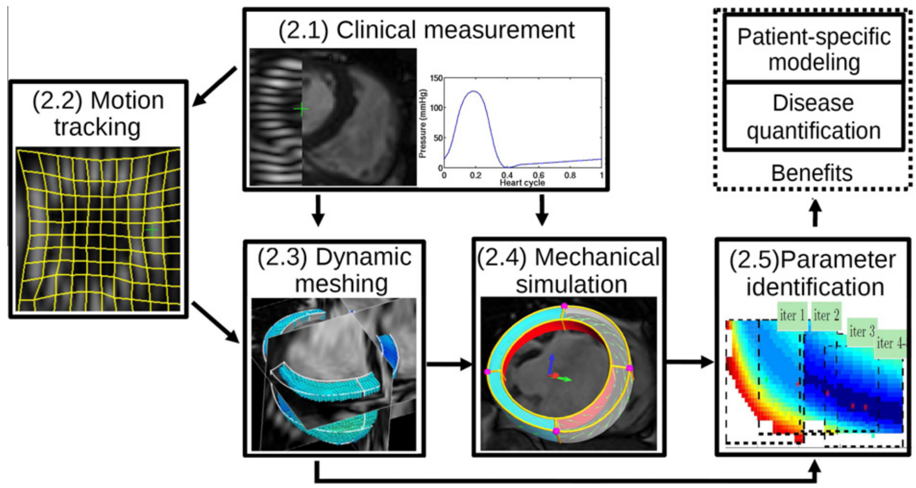

Fig. 1. Workflow of proposed data assimilation framework for patient-specific parameter estimation. The text labels correspond to the section number in this paper.

would have significant potential for application within clinical cardiology.

The focus of this study is to address this issue directly through the inclusion and estimation of an AT term during diastole. Specifically, built upon the parameter estimation framework for passive constitutive properties in our previous work (Xi et al., 2011b), we propose an approach to further estimate the residual AT during diastole to directly characterize the delayed relaxation often present in heart failure patients. We first undertake the necessary step for our estimation problem of reformulating the constitutive law to reveal and address the issue of the non-uniqueness of material parameters. Using this reformulated form, we then introduce an AT term in our mechanical model and estimate the residual AT in early diastole. Finally we apply this methodology to clinical cases with pressure, cine and tagged MRI measurements, with the results showing that estimated myocardial stiffness and residual AT appear to be promising candidates to delineate healthy and pathological patient cases.

2. Materials and methods

The constitutive parameters and residual AT are identified by comparing simulated diastolic inflation to a set of observed deformations extracted from combined cine and 3D tagged MRI data. Specifically, passive filling of the human left ventricle (LV) is simulated using patient-specific geometry, with the loading condition determined from LV cavity pressure recordings. The geometry are obtained with an automatic dynamic meshing process, which captures the LV anatomy using one frame of the cine MRI data. Fig. 1 schematically illustrates this complete process, where the numbered labels correspond to the subsequent sections in this paper.

2.1. Clinical measurements

The data used in this study were acquired from two patients selected for Cardiac Resynchronization Therapy (CRT) in St Thomas' Hospital, London and one healthy subject for control. This study conforms to the principles outlined in the Declaration of Helsinki and was carried out as part of a local ethics committee-approved protocol with informed consent obtained from the patients. Patient case 1 is a 74-year-old female with NYHA Class II heart failure despite optimal medical treatment. There was significant LV systolic dysfunction with an LV ejection fraction of 16% and QRS duration of 168 ms. The LV is significantly dilated with an end systolic volume (ESV) of 335 ml. Patient case 2, a 78-year-old male, has the same disease classification as case 1, with ejection fraction of 17% and an ESV of 186 ml. The control case used in this study is a healthy 36-year-old male.

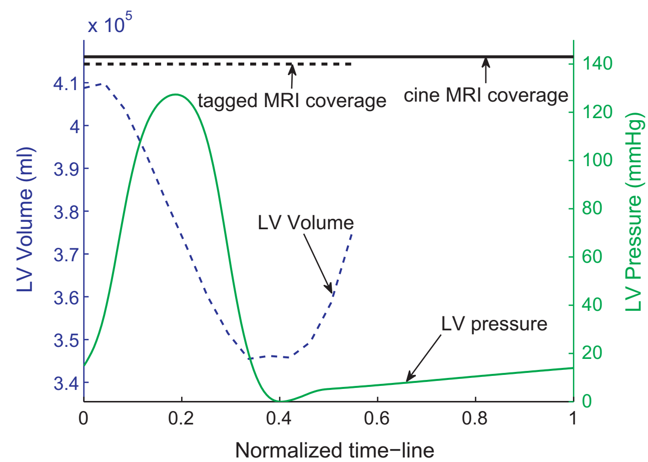

Fig. 2. The coverage of cine and tagged MRI, pressure transient, and derived volume transient for patient case 1. The *x*-axis is the normalized heart cycle (R–R interval). The top horizontal line shows the coverage of the 29 frames of cine MRI and the 23 frames of tagged MRI. The beginning of diastole is at the frame 18 of the tagged MRI sequence, and thus five frames at early diastole are available while the frame of end-diastole is assumed to be synchronous to the R wave. The volume transient is calculated as the LV cavity volume of the fitted FM meshes (described in Section 2.3.2). The pressure transient is the averaged value recorded over multiple heart cycles.

For each of these three data set, cardiac deformation is characterized by spatially aligned cine MRI (29 frames per heart cycle, short-axis view, vowel size $1.3 \times 1.3 \times 10$ mm) and 3D tagged MRI (23 frames per heart cycle, vowel size $0.96 \times 0.96 \times 0.96$ mm, tagging line width $\sim$5 vowels). The LV cavity pressure transient is obtained from the cardiac catheterization procedure (separately from the MR scan), when the rate of change of LV pressure is measured. Fig. 2 summarizes the data set of patient case 1. The diastolic cavity pressure for the healthy case is taken by digitalizing the data of a typical pressure profile (Klabunde, 2005, Chapter 4, p. 62). End diastolic pressure is 1.47 kPa for the control case, while cases 1 and 2 are 1.93 and 1.69 kPa respectively.

2.2. Myocardial motion tracking

Critical information for the guidance of mechanical parameter estimation are the 3-dimensional displacements of N tracked