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Detecting left ventricular impaired relaxation in cardiac MRI using moving mesh correspondences

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ARTICLE INFO

Article history:
Received 3 May 2015
Received in revised form
21 September 2015
Accepted 20 October 2015

Keywords:
Cardiac left ventricle
Diastolic function
Image registration
Image segmentation
Magnetic resonance imaging

ABSTRACT

Anatomical cine cardiovascular magnetic resonance (CMR) imaging is widely used to assess the systolic cardiac function because of its high soft tissue contrast. Assessment of diastolic LV function has not regularly been performed due the complex and time consuming procedures. This study presents a semi-automated assessment of the left ventricular (LV) diastolic function using anatomical short-axis cine CMR images. The proposed method is based on three main steps: (1) non-rigid registration, which yields a sequence of endocardial boundary points over the cardiac cycle based on a user-provided contour on the first frame; (2) LV volume and filling rate computations over the cardiac cycle; and (3) automated detection of the peak values of early (*E*) and late ventricular (*A*) filling waves. In 47 patients cine CMR imaging and Doppler-echocardiographic imaging were performed. CMR measurements of peak values of the E and A waves as well as the deceleration time were compared with the corresponding values obtained in Doppler-Echocardiography. For the *E*/*A* ratio the proposed algorithm for CMR yielded a Cohen's kappa measure of 0.70 and a Gwet's AC1 coefficient of 0.70. Conclusion: Semi-automated assessment of the left ventricular (LV) diastolic function using anatomical short-axis cine CMR images provides mitral inflow measurements comparable to Doppler-Echocardiography.

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http://dx.doi.org/10.1016/j.cmpb.2015.10.015
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1. Introduction

Most of the existing left ventricle (LV) assessment algorithms using cine cardiac magnetic resonance (CMR) focus on the *systolic function*, and are often limited to the analysis of regional wall motion abnormalities or the estimation of the ejection fraction [1–3]. However, the *diastolic function* is essential in the evaluation of various heart diseases, and several studies suggested that the assessment of the diastolic function is also important [4–7]. Heart failure with a preserved left ventricular ejection fraction represents approximately 40–50% of all cases of heart failure [7,8], and is increasing in prevalence among the senior population [9]. Furthermore, a distinction between systolic and diastolic heart failure is essential, given the importance of the therapeutic and prognostic differences between these two subsets of heart failures [10]. Therefore, early and accurate diagnosis of abnormalities in diastolic filling is of the utmost importance.

Although direct measurement of the LV filling pressures is preferable, the use of angiography is not ideal for routine clinical assessments as several non-invasive methodologies have become widely available [11]. Currently, 2D echocardiography using flow Doppler imaging is widely used to measure transmitral velocities. The existing echocardiography studies are based on Doppler measurements at the tips of the mitral valve leaflets to determine peak velocities of mitral inflow [9], Doppler echocardiography to estimate the mitral flow and pulmonary venous flow [12,13], and a color M-mode Doppler to estimate information such as the ventricular relaxation or compliance from transmitral velocity profile, among others. Despite these advances, transthoracic echocardiography (TTE) has important disadvantages, including a limited field of view due to the acoustic window, dependence on sample volume location, cosine θ errors relative to the flow direction, and the inability to image approximately 15–20% of the patients [5,11].

Although multiphase computed tomography (CT) can also be used for the analysis of the LV function, only a few studies were devoted to the analysis of the diastolic function. Boogers et al. presented a comparison between CT and 2D echocardiography using tissue Doppler imaging, noting good correlations for transmitral velocity, mitral septal tissue velocity, and estimation of the LV filling pressures [14].

Alternatively, CMR imaging allows for an exhaustive myocardial evaluation with high spatial resolution, and has several important advantages. They relax the need for geometric assumptions and afford an excellent image quality. Some CMR studies relied on phase contrast for the evaluation of the diastolic function [15–18,11]. In another study, a finite element based technique is used to estimate the diastolic dysfunction using tagged CMR images [19]. However, these CMR acquisition protocols are not commonly used in routine clinical practices due to their complex and time-consuming post processing and interpretation. Among other magnetic resonance sequences, anatomical cine CMR remains the most widely used sequence to assess the cardiac function [20]. Few notable exceptions that used the anatomical cine MR to assess the diastolic function include Wu et al. [21] who used long-axis views to compute mitral annulus sweep volume, and Mendoza et al. [22] who used short-axis view to compute LV volumes and filling rates. Analysis of the diastolic function using short-axis view of the anatomical cine CMR requires delineation of LV from hundreds of images,[1] making manual segmentation impractical for standard clinical applications. Therefore, automated segmentation is important for the assessment of the diastolic function [23].

This study proposes a new method to assess the LV impaired relaxation using short-axis cine CMR images. The proposed method consists of a semi-automated LV segmentation approach and an automated detection of peak values of early and late ventricular filling waves. Given a user-provided segmentation of a single frame in a cardiac sequence, the proposed segmentation approach delineates endocardial borders of the LV via point-to-point correspondences. The moving mesh framework proposed in this study is fundamentally different from previous approaches [24,25]. Based on the concept of equivalent volume elements of a compact Riemannian manifold [26] and yielding a unique solution by solving a div–curl system, the proposed point-to-point approach prevents mesh folding, i.e., grid lines of the same grid family will not cross each other, an essential attribute in tracking cardiac tissues from a sequence of images.

2. Method

The proposed diastolic function analysis algorithm consists of *preprocessing* and *detection of the E and A waves*, the early and late (atrial) ventricular filling velocities, based on the computation of the LV filling rate curve. The proposed approach allows for evaluating the diastolic function for all the patients who undergo an CMR scan, including those who may not be primarily referred for a diastolic function evaluation. The method is based on three main steps: (1) non-rigid registration, which yields a sequence of points over time, given a user-provided contour on the first frame; (2) computations of the LV filling rate and volume over the cardiac cycle; and (3) automatic detections of the maxima of the E and A waves.

2.1. *Preprocessing*

Given a user-provided segmentation of a single frame in a cardiac sequence, the proposed method segments endocardial borders of the LV via point-to-point correspondences (refer to Fig. 1). We propose to use a moving mesh (or grid generation) framework [26] to compute point-to-point correspondences between the kth image T_k and $(k+1)$th image T_{k+1} (for $k = 1, \ldots, K-1$) defined over $\Omega \subset \mathbb{R}^2$ (K is the total number of frames in a cardiac cycle), thereby obtaining a sequence of points over time (refer to Fig. 2). We state the problem as the optimization of a similarity/dissimilarity measure [27]:

$$\hat{\phi} = \arg\underset{\phi}{\text{opt}} \quad E_S(T_k, T_{k+1}, \phi(\xi)) \tag{1}$$

where $\xi \in \Omega$ denotes pixel location, $\phi : \Omega \to \Omega$ a transformation function and $E_S(\cdot)$ a measure of similarity. As this problem may not have a unique solution, we introduce in the following a

[1] Typically 200 images per subject.

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