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Registration of dynamic multiview 2D ultrasound and late gadolinium enhanced images of the heart: Application to hypertrophic cardiomyopathy characterization

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ABSTRACT

Describing and analyzing heart multiphysics requires the acquisition and fusion of multisensor cardiac images. Multisensor image fusion enables a combined analysis of these heterogeneous modalities. We propose to register intra-patient multiview 2D+t ultrasound (US) images with multiview late gadolinium-enhanced (LGE) images acquired during cardiac magnetic resonance imaging (MRI), in order to fuse mechanical and tissue state information. The proposed procedure registers both US and LGE to cine MRI. The correction of slice misalignment and the rigid registration of multiview LGE and cine MRI are studied, to select the most appropriate similarity measure. It showed that mutual information performs the best for LGE slice misalignment correction and for LGE and cine registration. Concerning US registration, dynamic endocardial contours resulting from speckle tracking echocardiography were exploited in a geometry-based dynamic registration. We propose the use of an adapted dynamic time warping procedure to synchronize cardiac dynamics in multiview US and cine MRI. The registration of US and LGE MRI was evaluated on a dataset of patients with hypertrophic cardiomyopathy. A visual assessment of 330 left ventricular regions from US images of 28 patients resulted in 92.7% of regions successfully aligned with cardiac structures in LGE. Successfully-aligned regions were then used to evaluate the abilities of strain indicators to predict the presence of fibrosis. Longitudinal peak-strain and peak-delay of aligned left ventricular regions were computed from corresponding regional strain curves from US. The Mann–Withney test proved that the expected values of these indicators change between the populations of regions with and without fibrosis ($p < 0.01$). ROC curves otherwise proved that the presence of fibrosis is one factor amongst others which modifies longitudinal peak-strain and peak-delay.

1. Introduction

The heart is a complex organ involving and coupling different physical phenomena that can be assessed using multisensor cardiac imaging. The fusion of such multisensor information enables the description of heart multiphysics and the assessment of relationships between cardiac image modalities (e.g. complementarity or redundancy). For this purpose, image registration is required. In this work, we propose a method to register intra-patient cardiac 2D ultrasound (US) with late gadolinium-enhanced (LGE) magnetic resonance imaging (MRI). Indeed, dynamic 2D US is the gold standard modality to assess myocardial strain and LGE provide information about myocardial viability. But the relationship between these descriptors remain unclear. We aim to fuse these modalities to evaluate the alteration of US strain with regards to the presence of fibrosis in LGE. We propose to consider cine MRI as an intermediate image for the registration process to overcome the challenges of the multimodal registration of 2D US and 3D LGE.

LGE and 2D US images are acquired following multiple views (e.g. short axis, four-chamber, two-chamber) of the left ventricle (LV). US views, however, usually do not match MRI views. As a consequence, some structures are not well represented (e.g. the apical zone in MRI short axis view) or are distorted due to field-of-view constraints (e.g. the apical zone in apical long axis view US using transthoracic probes). Moreover, their multimodal nature, difference in temporal

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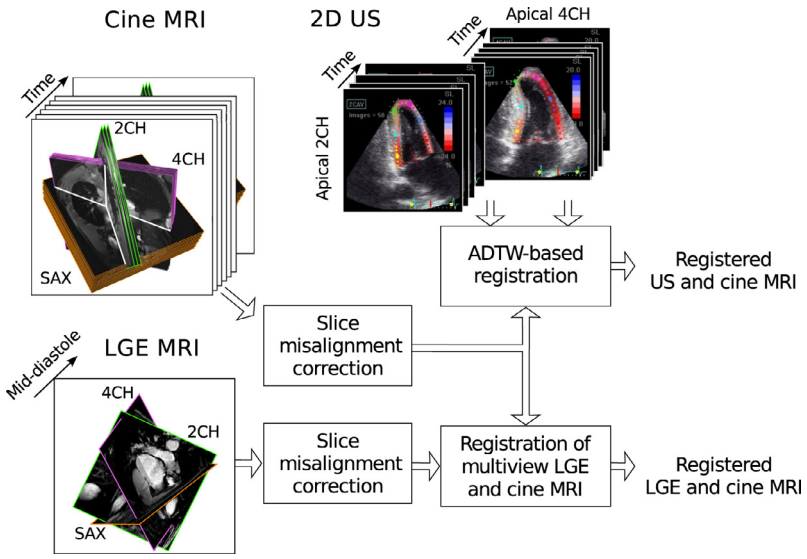

Fig. 1. Image registration framework of intra-patient 2D US and LGE MRI. Cine MRI is used as intermediary modality. It is set as the reference image.

and spatial resolution (dynamic 2D US vs static 3D LGE), the low US image quality and the presence of enhanced regions in LGE also hinder their registration.

Cine MRI is a good intermediate between US and LGE because US and cine are dynamic and because LGE is close to cine. On one hand, a dynamic registration approach of dynamic US and cine images yields a more robust spatial alignment, because the information concerning LV deformation is exploited. However, these images are not simultaneously acquired and cardiac dynamics change over time in a non-linear fashion (e.g. longer contraction and shorter relaxation). Consequently, this registration requires the synchronization of US and cine images. On the other hand, cine and LGE are acquired during the same MRI examination; thus, a rigid registration approach can be considered to align them. Nevertheless, they are acquired during multiple heartbeats, which results in potential slice misalignment. Then, appropriate similarity measures must be selected to correct for slice misalignment and to register LGE and cine MRI.

We propose an intra-patient registration procedure of both LGE and 2D US, with cine MRI. This aims to improve US-to-LGE registration by exploiting LV deformation. The registration procedure has been divided into three steps: (i) correction of slice misalignment in LGE and cine MRI, (ii) registration of LGE and cine MRI, and (iii) dynamic registration of US and cine MRI. One contribution of this paper concerns selecting the best similarity measure to correct and register LGE and cine MRI. US-to-cine registration relies on the Dynamic Time Warping procedure (DTW) to compute a spatiotemporal similarity measure from the Fourier descriptors of input LV contours (Tavard et al., 2014). The DTW is an effective procedure to match dynamic time variations between time series (e.g. due to contraction and elongation of cardiac phases); however, it can lead to the presence of artifacts in the synchronization of cardiac dynamics. In this paper, we propose to adapt the DTW procedure to compute a coherent warping of cardiac phases in US and cine images.

The proposed registration method is presented in the next section in three steps: slice misalignment correction of LGE and cine MRI (Section 2.1), registration of LGE and cine MRI (Section 2.2), and dynamic registration of 2D US and cine MRI (Section 2.3). The evaluation of image registration procedures is presented in Section 3. This focuses on selecting the best similarity measure to correct LGE slice misalignment and to align LGE and cine MRI, and on the evaluation of US-to-LGE registration. Section 3.4 is dedicated to an application of the proposed registration workflow. US and LGE fusion enabled to study if the alteration of strain-derived indicators is caused by the presence of fibrosis in patients with hypertrophic cardiomyopathy (HCM). The conclusion and perspectives are presented in Section 4.

2. Methods

Fig. 1 presents the proposed registration framework. The cine short axis view (SAX) image is used as the reference image to register both LGE and US. The acquisition of US, cine and LGE is described in Section 3.1. The registration procedure corrects for slice misalignment in LGE and cine MRI and then registers corrected multiview images. US and corrected cine-SAX are then aligned using a registration approach based on an adapted DTW (ADTW) procedure. Below we present these three steps.

2.1. Slice misalignment correction of LGE and cine MRI

MRI systems image one cardiac phase during multiple heartbeats and, even under breath-hold acquisitions, patient physiological motion (mainly breathing) cannot be completely avoided, resulting in rigid slice misalignment (Prieto, 2013; McLeish et al., 2002). Thus, slice misalignment must be corrected to exploit the information that they contain. The registration of multiview cine images has been used to find the spatial transformation per slice that corrects for out-of-plane and/or in-plane misalignments (Carminati et al., 2012; Elen et al., 2010; Slomka et al., 2007; Lötjönen et al., 2005). (Slomka et al., 2007) proposed a correction approach with two registration steps. In the first step, two-chamber view (2CH) and four-chamber view (4CH) images, each with only one slice, are registered. In the second step, they are fixed to correct each slice in the SAX image. (Elen et al., 2010) used a combined approach that corrects input slices in a single registration. They also reported a comprehensive study of similarity measures showing that absolute voxel differences and normalized mutual information (NMI) perform the best. Few works have been reported for LGE correction. (Wei et al., 2013) corrected for in-plane misalignments in LGE using a metric including both, iconic similarity and continuity of the heart. This requires the delineation of heart structures which is difficult in the presence of fibrosis/scar.

We use a sequence of three registration steps to correct for slice misalignments in 2CH, 4CH and SAX cine/LGE MRI. In the first step, the 4CH image is corrected using the median slice of 2CH as the reference image. In the second step, the corrected 4CH image is used to correct the 2CH image. In the third step, the SAX image is corrected