Dynamic Registration of Multiple-view-US and MRI for the Characterization of Hypertrophic Cardiomyopathy

Julián Betancur\textsuperscript{1,2}, Antoine Simon\textsuperscript{1,2}, Frederic Schnell\textsuperscript{1,2,3}, François Tavard\textsuperscript{1,2}, Erwan Donal\textsuperscript{1,2,4}, Alfredo I. Hernandez\textsuperscript{1,2}, Mireille Garreau\textsuperscript{1,2}

\textsuperscript{1} INSERM, UMR 1099, Rennes, France
\textsuperscript{2} Université de Rennes 1, LTSI, Rennes, France
\textsuperscript{3} Université de Rennes 1, Lab. Physiologie Médicale, Rennes, France
\textsuperscript{4} CHU Rennes, Service de Cardiologie, Rennes, France

Abstract

The relationship between strain and fibrosis for patients with hypertrophic cardiomyopathy (HCM) remains unclear. This work aims to fuse (i) myocardial fibrosis assessed from late-gadolinium-enhanced MRI (LGE) sequence and, (ii) myocardial strain from multiple-view 2D speckle tracking echocardiography (STE). A spatio-temporal alignment is performed between segmented data extracted from cine-MRI short-axis-view and STE apical two- and four-chamber views. Dynamic Time Warping (DTW) and Fourier descriptors are used to handle the non-linear relationship between the cardiac phases of input sequences and the different levels of details provided by the two modalities. An expert evaluated the results visually, leading to a percentage of exploitable cardiac segments of 87%. Finally, MRI-LGE image was superimposed to the corresponding mid-diastolic STE contours to perform the combined tissue and strain analysis. Results on ten patients suggest that myocardial fibrosis is associated with a decrease in longitudinal strain and therefore that STE can be used to detect myocardial fibrosis.

1. Introduction

Hypertrophic cardiomyopathy (HCM) is a common genetic cardiovascular disease with a worldwide prevalence of 0.2% [1]. HCM is characterized by left ventricle (LV) hypertrophy and is usually recognized by maximal LV wall thickness $\geq 15\text{mm}$ based on echocardiography, although cardiac magnetic resonance (CMR) is now used with increasing frequency [2].

Approximately half of patients with HCM have late gadolinium enhancement (LGE) suggestive of areas of fibrosis [3]. Previous studies demonstrated that the extent of LGE was correlated with LV systolic and diastolic dysfunction as well as adverse cardiac events such as sudden cardiac death, fatal arrhythmia or worsening heart failure [4].

Previous studies reported that regional myocardial fibrosis affects regional myocardial strain and wall thickening [5]. Two-dimensional speckle-tracking echocardiography (STE) had shown to provide an angle-independent, rapid and accurate method for strain measurement [6]. The description of the relationship between myocardial strain and the macroscopic fibrosis would allow a low cost and early characterization of the myocardial tissue and an improvement in diagnostic. For this purpose, the fusion of speckle tracking echocardiography and the LGE magnetic resonance (LGE-MR) sequences should be considered to establish and describe the aforementioned relationship.

The static registration of the LV surface from LGE-MR image (routinely acquired at mid-diastole) with its corresponding STE contour is difficult because of the lack of dissimilarity in LV geometry (i.e. LV smoothness and symmetry). To overcome this difficulty, one option is to consider more information by taking advantage of the temporal dimension. All the acquired sequences are then used in a spatio-temporal registration approach [7]. Although some iconic registration approaches have been reported [8], a surface-based approach was selected here in order to use the available STE data. Different methods could here be used to describe and compare LV contours [9]. Fourier descriptors (FDs) were selected because the comparison of contours obtained by different modalities becomes straightforward. However, because STE and MRI are not simultaneously acquired, the corresponding cardiac cycles may be different, and with a potential non-linear relationship. A temporal alignment is therefore computed by using the dynamic time warping (DTW) method [10], which allows to compare the two dynamic Fourier representations.

This paper presents an approach to fuse mechanical (strain) and tissue information from STE and MRI-LGE sequences. It is based on a spatio-temporal rigid regis-
tration of contours and surfaces extracted from ultrasound (US) and MRI acquisitions, respectively. The paper is organized as follows: the considered data is presented firstly, then the proposed methods are described with a focus on the spatio-temporal registration using Fourier descriptors and DTW. Finally, an evaluation of the registration is proposed and the results for ten HCM patients are presented and discussed, to later derive a conclusion and some perspectives.

2. Materials and methods

2.1. Data

Data corresponding to ten patients has been considered in this work. The diagnosis of HCM followed recent guidelines [2]. Besides, patients have some degree of fibrosis in LV myocardium assessed from MR-LGE.

US four- and two-chambers-view (US-2CH and US-4CH, 56 to 82 frames) images were acquired at rest on a GE Vivid 7 station (GE Healthcare, Horten, Norway). The end-systole (ES) phase was determined using the ECG and the closure of the aortic valve. Then, the STE output contours were generated and exported for the RR-interval (using the peak of R-wave). Moreover, the strain curves associated to the classical cardiac segments were computed and exported.

Cine-MR sequences (Short axis view (MRI-SAX), 2- and 4-chambers views (MRI-2CH and MRI-4CH) of the left ventricle were also acquired (ECG gated, 30 phases). ES phase was determined on MR-SAX images. Besides, late-gadolinium-enhanced (MRI-LGE) images were acquired at mid-diastole for the same views and were used to assess the presence of fibrosis. The endocardium of the LV has been segmented on the MRI-SAX images using the ITK-SNAP implementation of deformable surfaces [11].

2.2. Spatio-temporal registration

A spatio-temporal registration method is used to register jointly: (i) the 2D contour of the endocardium segmented from US-2CH and US-4CH; (ii) the 3D surface segmented from MRI-SAX (cf. Fig. 1). This method corresponds to a rigid spatial registration with an underlying non-linear temporal alignment. For this purpose, the two US acquisition planes are searched for in the MRI reference system. It relies on the optimization of a metric quantifying the reliability of an acquisition plane by evaluating the correspondence between two dynamic contours (2D+t): (i) one of the two dynamic contours segmented from US; (ii) the dynamic contour resulting from the slicing, with the evaluated acquisition plane, of the dynamic surface segmented from MRI-SAX. Using Dynamic Time Warping and Fourier descriptors, the metric computation initiates by estimating the most reliable temporal alignment between both contour sequences and then quantifies the quality of the geometric correspondence between them.

2.2.1. Metric computation: Fourier descriptors and Dynamic Time Warping

A metric is computed to evaluate the correspondence between two dynamic contours, the first one segmented from US (US-2CH or US-4CH), and the second one resulting from the slicing of the dynamic surface segmented from cine-MRI.

The levels of details rendered by the two considered modalities are very different: US contours are smoother than MRI surfaces. A Fourier decomposition is therefore performed in order to weight the contribution of their global and fine shape details. A previous study suggested that the optimal number of descriptors to describe both contours is 60 [12].

In order to determine the non-linear temporal alignment between both dynamic contours, dynamic temporal warping (DTW) is performed. DTW is based on the search of a minimal path in a matrix quantifying the likelihood of the temporal correspondence of each couple of time-samples. This distance is defined by:

$$d(\hat{U}_i, \hat{S}_j) = \sum_{k=0}^{59} \frac{1}{k+1} \left| \hat{U}_{ik} - \hat{S}_{jk}(\nu) \right|, \quad (1)$$

where $\hat{U}_{ik}$ and $\hat{S}_{jk}(\nu)$ are the $k$-th FD of the STE contour at time $i$ $\hat{U}_i$ and of the MRI-SAX contour at time $j$ $\hat{S}_j$, respectively. Moreover, this matrix is masked in order to limit the search space to a realistic domain. Dynamic programming is used to search for the optimal path in this
matrix, defining the temporal alignment between both sequences.

The sum of $d(\hat{U}_i, \hat{S}_j)$ over the whole optimal path is finally used as the similarity measure of the evaluated US acquisition plane.

### 2.2.2. Metric optimization

US-2CH and US-4CH acquisition planes are optimized simultaneously. They are defined by their origin (which is considered as being the LV apex) and their normal. They are initialized by manually selecting the apex and by using the acquisition plane of MRI-2CH and MRI-4CH.

The position of the apex and the plane normals are then optimized using a simplex algorithm. The optimized metric is the sum of the previously described metric computed for the two US acquisitions planes. The searching space is constrained by checking that: (i) the apex has to be included in a sphere centered at the initial apex and of a radius of 10 mm; (ii) the plane normals have to be included in a cone whose vertex is localized at the apex, with an angle of 10°, and oriented towards the initial plane orientation.

Once the acquisition planes have been optimized, the two considered contours (US-2CH or US-4CH, and the MR contour resulting from the slicing) have to be aligned within the plane. They are positioned according to the apex and their long axis.

### 2.3. Strain/fibrosis relationship

In this work, only patients with good spatial agreement between cine-MRI images and LGE-MR images were considered. Therefore, once the spatial transformation between the US acquisitions and the MRI-SAX has been optimized, it is considered as being also consistent with MRI-LGE. Then, MRI-LGE image was superimposed to the corresponding mid-diastolic STE contour to assess the feasibility of performing the combined tissue and strain analysis.

For each segment of the STE contours (6 segments per contour), two descriptors are available: (i) strain curve measured in US, from which the peak longitudinal strain value is computed; (ii) presence or absence of fibrosis visually assessed from MRI-LGE. A statistical analysis was carried out to determine the relationship between peak strain and fibrosis.

### 3. Results

#### 3.1. Evaluation of the temporal alignment

In order to evaluate the quality of the temporal alignment provided by DTW, a study was carried out using data of four patients: the end-systole phase were manually selected on both acquisitions and the agreement with the DTW result was assessed for the two modalities in terms of misalignment between the two corresponding instants, measured as a percentage of the RR-interval (0% being the best value). An average misalignment of 4.4% was obtained for US and of 10.5% for MRI.

### 3.2. Qualitative evaluation of the registration

After the alignment of US acquisitions with MRI-SAX, a cardiologist assessed the number of LV segments aligned correctly. Over a total of 120 segments (10 patients, 2 US views per patient, 6 segments per view), 105 segments (87.5%) were well aligned. All not-aligned segments were apical segments. This can be explained by the low quality of apical segment representation in US images. Only well aligned segments were used in further analysis.

### 3.3. Strain and fibrosis relationship

Considering the data from the 10 patients, 27 segments of STE contour (29.7%) were associated with fibrosis on MRI. Figure 2 shows two patients with fibrosis affecting two ventricular segments of each patient. The strain curves associated to these four segments have a noticeably lower amplitude than the other ones.
The mean value of the peak strain associated to segments with fibrosis was $-8.5 \pm 3.8\%$. The mean value associated to segments without fibrosis was $-17.6 \pm 5.0\%$. The difference between the two groups was statistically significant (student’s t-test, p<0.000001).

4. Conclusions and perspectives

A method for simultaneous registration of 2CH/4CH US acquisitions and cine-MRI was presented. A spatio-temporal registration approach based on Fourier descriptors and DTW was used. It allowed to consider all available dynamic information. The final goal is to fuse mechanical and tissue information from HCM patients. Results proved that this spatio-temporal registration permits a satisfactory association between STE and MRI-LGE information. Further analysis on ten patients suggested a correlation between myocardial fibrosis and the change of the strain curve. The clinical significance of these results will be discussed in EuroEcho-Imaging 2013 [13]. This study will include more HCM patients with and without fibrosis in order to validate the strain/fibrosis correlation. Also, we will evaluate the benefit of using an iconic registration instead of the geometric approach presented here. The intersequence registration of cine-MRI and MRI-LGE will be included as well.

References


Address for correspondence:
Julián Betancur
LTSI, Bât. 22, Campus Beaulieu, 35000 Rennes, FRANCE
julian.betancur@univ-rennes1.fr, julianbetancur@gmail.com