Cardiac Motion Analysis from Cine MR Sequences Using Non-Rigid Registration Techniques

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Abstract

The objective of this work is to evaluate the feasibility of using non-rigid registration techniques to estimates myocardial motion from CINE-MR images without user interaction.

Myocardial displacement field was obtained using a pair-wise non rigid registration technique that computes incremental motion for every consecutive pair of images in the sequence. We use a semi-local parametric deformation model that balances both local and global motion estimation. This analytical representation provides an excellent frame work to derive myocardial function parameters such as strain.

In order to assess the applicability of the method we measure and compare radial displacement (Dr) and strain (Sr) in a total number of 56 normokinetic segments and 26 hypokinetic segments. These measurements correlate well with previous functional knowledge of the myocardial function from tagged MR data.

1. Introduction

The usefulness of myocardial displacement and strain quantification for the assessment of regional myocardial deformation using tagged MR techniques has been widely demonstrated [1-3]. However, the accuracy and feasibility of measuring 2D myocardial motion fields using conventional CINE MR hasn't been deeply studied. Therefore, the development of two-dimensional (2D) methods for the assessment of regional deformation analysis in CINE MR images.

Previous technique working on CINE MR images have been approached using segmentation techniques, such as deformation models [4] and level sets techniques[5]. Mechanical models have been also used including mechanical constraints [6]. Non rigid registration techniques have been also investigated in 3D+T volumes using mutual information techniques[7]. The feasibility of using these techniques in 2D datasets hasn't been previously investigated.

Our work proposes to use non-rigid registration techniques to estimate the myocardial motion fields from conventional CINE MR short axis sequences. The key feature of the algorithm is the use of a semi-local parametric transformation model based on Bspline bases functions. The proposed method has been applied to the analysis of systolic myocardial function in data from 26 patients and 56 healthy volunteers.

2. Myocardial motion estimation

Myocardial motion is computed using a non-rigid registration technique across the whole sequence on a frame–to-frame basis, as previously proposed to compute motion on echocardiographic sequences [8, 9]. The key feature of this method is the use of an analytical representation of the myocardial displacement field based on a semi-local parametric model using B-splines. The displacement field and the strain tensor are obtained from the analytical expression of the displacement field and its spatial gradient. Robustness and speed are achieved by introducing a multiresolution-optimization strategy.

2.1. Problem outline

Given an image sequence $f(t,\boldsymbol{x})$, the goal is to estimate a dense displacement field $\boldsymbol{g}(t,\boldsymbol{x})$ over the whole sequence. Briefly, we choose to represent the movement with respect to the first frame of the sequence: a point at coordinate x in the first frame ($t = t0$) will move to the location $\boldsymbol{g}(t,\boldsymbol{x})$ at time t. This objective is attained by means of non-rigid registration of consecutive pairs of images (Figure 1).

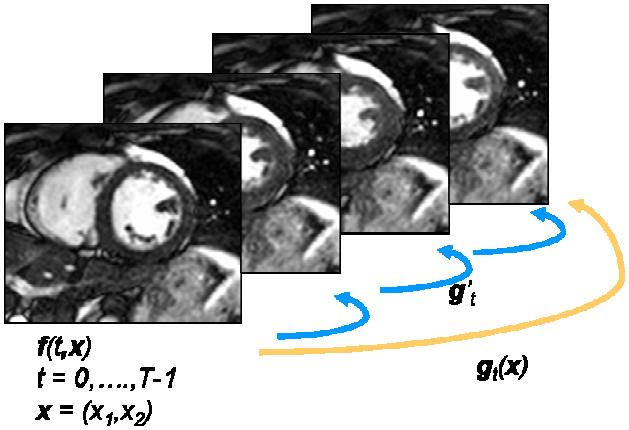

Figure 1: Global scheme of the proposed methodology. Motion field is computed accumulating the consecutive contributions of interframe displacements.

The method computes $\mathbf{g}(t,\mathbf{x})$ as a series of transformations between consecutive pairs of images $\mathbf{g'}_t(\mathbf{x})$. The formulation is

$$\mathbf{g}(t,\mathbf{x})=\mathbf{g}_t(\mathbf{x}) \text{ where } t \in \{0, ...,T-1\} \text{ and } \mathbf{x}=(x_1,x_2) \quad (1)$$

$$\mathbf{g}_t(\mathbf{x}) = \mathbf{g'}_t(\mathbf{x}_{t-1}) \text{ where } \mathbf{x}_{t-1}=g_{t-1}(\mathbf{x}) \text{ and } \mathbf{g}_0(\mathbf{x}) = \mathbf{x}$$

The transformation between consecutive frames $\mathbf{g'}_t$ is defined as a linear combination of B-spline basis functions[8, 10, 11] :

$$\mathbf{g'}_t(\mathbf{x}) = \Sigma\, \mathbf{c_j}\, \beta_r(\mathbf{x}/h-\mathbf{j}) \quad (2)$$

Strain (S) is calculated from the dense displacement field using a Green-Lagrange Strain Tensor:

$$\mathbf{S} = \tfrac{1}{2}(\mathbf{F}^T\mathbf{F}- \mathbf{I}) \quad (3)$$

$\mathbf{F}$ being the deformation gradient tensor:

$$\mathbf{F} = \nabla_x \mathbf{g} + \mathbf{I} = \begin{bmatrix} \partial \mathbf{g}_1 / \partial \mathbf{x}_1 & \partial \mathbf{g}_1 / \partial \mathbf{x}_2 \\ \partial \mathbf{g}_2 / \partial \mathbf{x}_1 & \partial \mathbf{g}_2 / \partial \mathbf{x}_2 \end{bmatrix} + \mathbf{I} \quad (4)$$

As $\mathbf{g}$ is defined using B-spline functions, its derivatives ($\partial \mathbf{g}_1 / \partial \mathbf{x}_1$) can be analytically computed.

The analytical Bspline parametric model was also used to represent a continuous version of the sequence. A multiresolution strategy assured fast and robust convergence.

The displacement field was also constrained using a priori knowledge about the cardiac motion field. Firstly, the motion at the reference frame f(0, x) must be zero and, secondly, we impose the cyclic behavior as $\mathbf{g}(0, \mathbf{x}) = \mathbf{g}(T, \mathbf{x})$. This last constraint is achieved by performing the registration process in both directions (forward $\mathbf{g}^f_t(\mathbf{x})$ and backward) $\mathbf{g}^b_t(\mathbf{x})$, obtaining two estimations of the displacement at a given time t. The final estimation is computed as a weighted linear combination of both estimates, which is the maximum likelihood (ML) estimate of the motion.

$$\mathbf{g}_t(\mathbf{x}) = \omega_t\, \mathbf{g}^f_t(\mathbf{x}) + (1- \omega_t)\, \mathbf{g}^b_t(\mathbf{x}) \text{ with } \omega_t = (T-t) / T \quad (5)$$

2.2. Imaging

All the scans were performed in a Philips Intera 1.5 T (Philips Medical Systems, The Netherlands) and with a five elements phased-array coil dedicated to cardiac imaging. The scans were performed using a breath hold Balance Fast Field Echo (B-FFE) sequence. Parallel imaging was used to be able to acquire a higher number of frames per sequence. More than 60 frames per cycle were actually acquired.

2.3. Data analysis

A total number of 56 normokinetic segments and 26 hypokinetic segments were analyzed from the acquired short axis images. The segments were manually delineated in the first frame of the sequence and propagated through time using the resultant myocardial field. The location of the left ventricular long axis on the slice was also provided by the user in order to compute the proper projections of the radial and circumpherential components. Mean displacement and strain tensor were obtained for each segment extracting the radial and circumpherential components of the mean segment displacement and strain. Radial displacement and strain time evolution curves where analyzed computing radial peak displacement (Dr) and radial peak strain (Sr). All the analysis was performed using a locally developed software platform [12] properly adapted to process CINE MR sequences.

3. Results

Tracking results of the proposed methodology were visualized observing the tracking results on the segment contours after applying the recovered motion field. Figure 2 shows the 6 segments defined in the first image of the sequence and the resultant moved contours for three different frames of the cardiac cycle (frames 5, 10 and 20). Total number of frames in the sequence was 60.

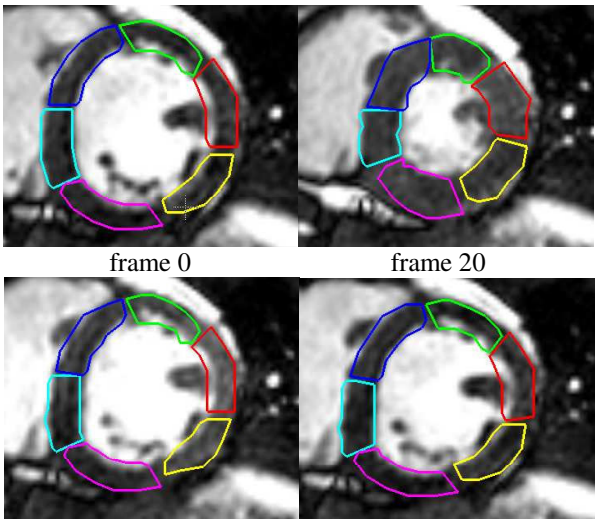

Figure 2: Visualization of the tracking results in a normal volunteer sequence of 60 frames. Segments were defined in the first frame of the sequence (top-left) and tracked using the recovered motion field to the rest of the sequence.

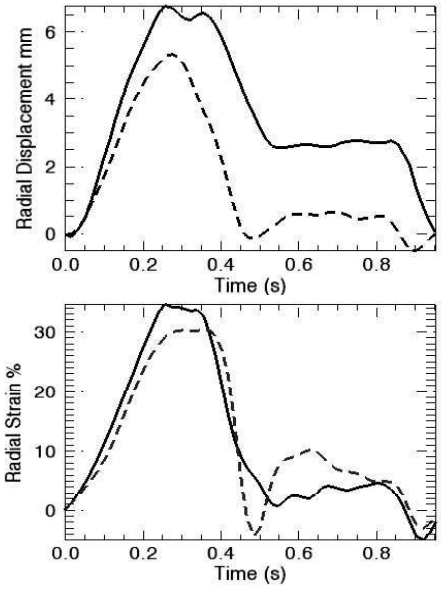

Figure 3: Healthy volunteer: Radial displacement (top) and strain (bottom) time evolution curves for two segments (septum: solid line; lateral wall : dotted line).

Figure 3 shows the radial displacement and strain time evolution curves extracted for two segments (septum and lateral wall) in a mid ventricular slice in a healthy volunteer. Figure 4 shows the corresponding curves for an ischemic patient with severe diskinesia in the septum.

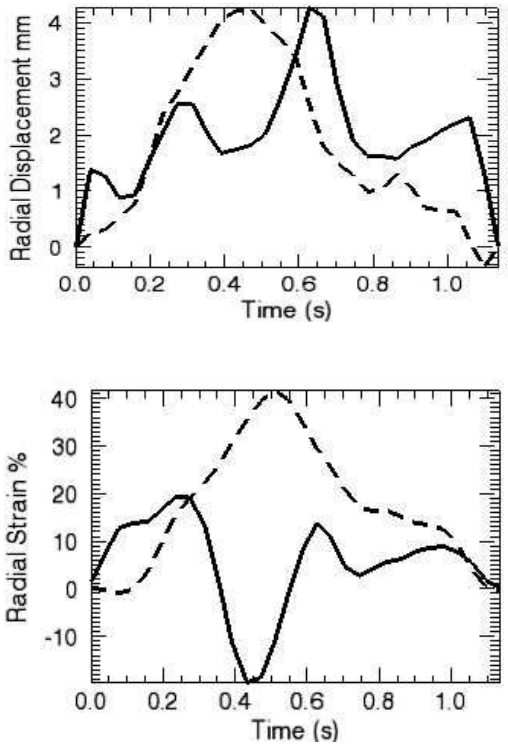

Figure 4: Ischemic patient: Radial displacement (top) and strain (bottom) time evolution curves for two segments (septum: solid line; lateral wall : dotted line).

Numerical results of the analysis of normokinetic and hypokinetic segments are shown in table 1. The measured values are consistent with respect to previous literature using Tagging techniques.

Table 1: Numerical results of peak radial displacement (Dr) and peak radial strain (Sr) for the 82 segments analyzed.

Segments	Dr (mm)	Sr (%)
Normokinetic N= 56	5.3±1.5	48.3±11.6
Hypokinetic N=26	2.8±1.9	20.6±10.9

4. Discussion and conclusions

In this work we have presented a non-rigid based method to automatically estimate 2D myocardial motion fields from CINE MR images. The method does not

require any presegmention step

Main limitations of the proposed techniques are the intrinsic limitations in the CINE MR data. Firstly the motion observed in a 2D sequence is a combination of the myocardial contraction and the out of plane motion. In order to reduce the effect of out of plane motion in the measurement slice following techniques and navigator echos may be incorporated in the acquisition. As a second limitation is the lack of resolution in the images to discriminate between myocardial tissue, endocardial and trabecular tissue. The elastic properties of these tissues are very different, however the image features do not represent them differently, and therefore the measured motion takes into account the behaviour of the three tissues as a whole. As demonstrated in [13] this effect can be significant.

As main occlusion we could state that obtaining radial displacement and strain parameters from conventional CINE MR imaging using spatio-temporal non-rigid registration techniques is feasible and allows quantifying regional myocardial function, overcoming the frame rate limitations of Tagged MR. Further research is guaranteed to assess the accuracy and feasibility of measuring circumferential motion and strain using CINE MR sequences.

Acknowledgements

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