Detecting the onset of myocardial contraction for establishing inverse electro-mechanical coupling in XMR-guided RF ablation

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Introduction

Measurements of subtle changes in motion patterns of the heart can be used to detect the onset of diseases such as arrhythmia, ischaemia, and infarct, as well as to follow up medical treatment using either drugs or surgical intervention. One such example of disease with associated changes in motion patterns are tachyarrhythmias: pathological fast heart rhythm, often the result of abnormal paths of conduction. In patients for whom drug treatment is ineffective and those with life threatening arrhythmia, radio-frequency (RF) ablation is the treatment of choice. During RF ablation the arrhythmia substrate is first assessed by an electrophysiological study. Treatment then follows by applying a RF current via an ablation electrode which induces hyperthermia and destruction of the abnormally conducting areas. These procedures are typically carried out under x-ray (2D) guidance, leading to errors in the location of the abnormal areas as well as to excessive x-ray exposure for the patient.

One of our goals is to provide pre- and intra-operative 3D MR guidance [1] in XMR systems (combined X-ray and MRI room) by locating myocardial regions with abnormal electrical conduction patterns. We address the inverse electro-mechanical relation by using motion in order to infer electrical activation and propagation patterns. For this purpose we define a probabilistic measure of the onset of regional myocardial motion derived from motion fields. The 3D motion fields are obtained using non-rigid registration of tagged MR sequences to track the heart. We also compare regional motion between two different image acquisitions, thus assisting in diagnosing arrhythmia, in follow up of treatment, and particularly in determining whether the electro-physiological intervention succeeded.

Methods

Image registration for tracking: We use a non-rigid registration algorithm [2] to track the motion and deformation of the heart in a sequence of 3D short- and long-axis tagged MR images. The goal of the non-rigid registration is to align each time frame of the tagged MR image sequence with the end-systolic time frame of the image sequence by maximising the normalised mutual information of both time frames. To model cardiac motion we use a free-form deformation based on cubic B-splines. The output of the registration is a (time varying) 3D motion field (Figure 1).

Image segmentation and coordinate system: Using the computed 3D motion field, a manual segmentation of the myocardium at end-diastole is automatically propagated to define the myocardial surface over the entire cardiac cycle. A cylindrical coordinate system (the z-axis aligned with the long-axis of the left ventricle (LV)) is used to introduce a common reference system for comparing the motion fields corresponding to different image acquisitions, thus minimising the effect of potential misregistration due to patient motion after the catheter intervention. We also use this coordinate system to subdivide the myocardium into 12 meaningful regions with 4 sections around the z-axis that roughly correspond to septum, lateral, anterior and posterior walls, and 3 sections along the z-axis, corresponding to base, middle region and apex (Figure 1).

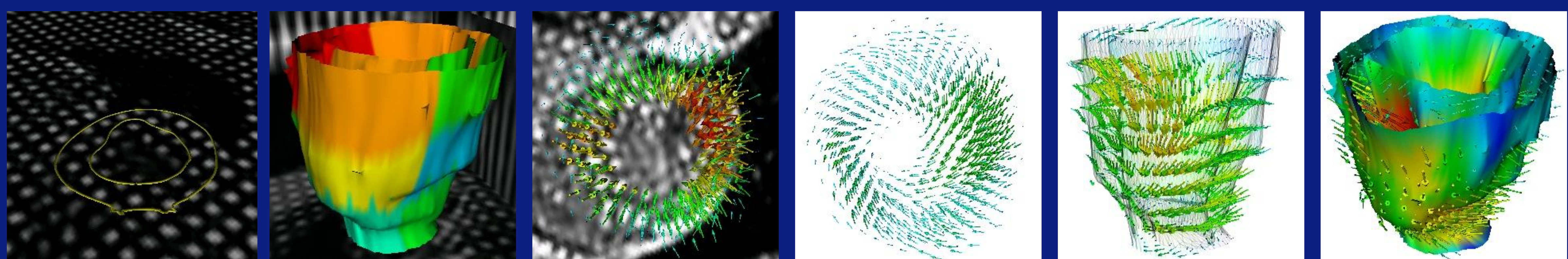

Figure 1. Segmentation and motion tracking, The first image shows a tagged plane with a 2D segmented contour, while the second shows the segmented end-diastolic 3D myocardial (LV) surface subdivided in 12 segments. The other images show the extracted motion field and the mapped values onto the automatically propagated myocardial surface.

Motion change and Activation: Displacement (wall excursion), strain and their rate of change are computed for each voxel and the values averaged for each of the myocardial segments, for every time frame during the cardiac cycle. To evaluate changes in the motion patterns between two data sets, a statistical measure is derived from the above combined quantities and the segment is assigned a measure of motion change and classified as having either no, small or significant changes [4]. Also a probabilistic measure of the activation of every segment at every time during the cycle is defined in terms of the motion field and the regional and global times of end diastole. Thus, for a given probability threshold value between 0 and 1, every region is assigned a time of activation. The isochrones representation shows these times of activation (Figure 4).

Synthetic images: In order to evaluate the proposed methodology in a controlled case where the ground truth was available we also implemented and modified a cardiac motion simulator for tagged MRI [3]. Two sequences of synthetic tagged LV images were produced: a 'post-intervention' (normal) sequence using the standard parameters, and a 'pre-intervention' (abnormal) sequence in which the motion parameters were modified in a small region of the myocardium by moving the phase of the contraction and changing the magnitude of the motion (Figure 2).

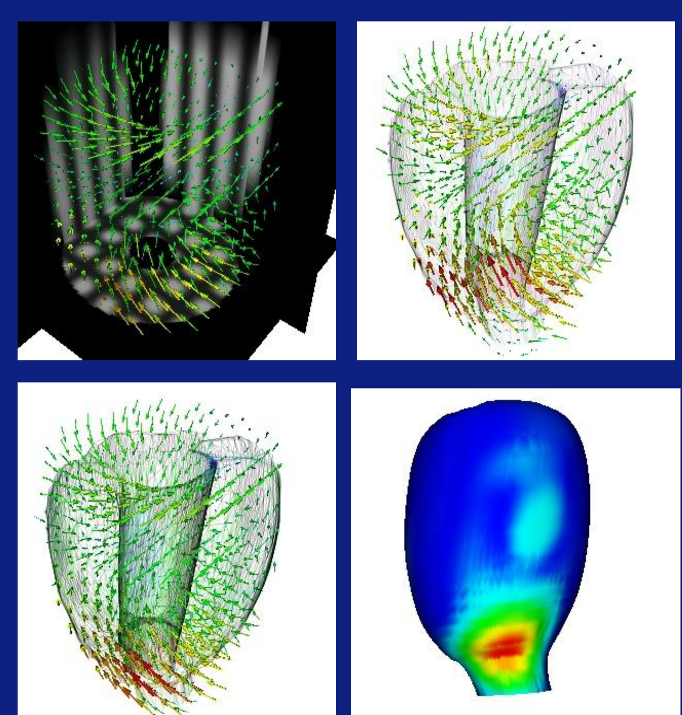

Figure 2: Synthetic cardiac tagged MR images with the extracted motion fields, before and after introducing the region with abnormal motion, and motion difference surface.

Experiments and results

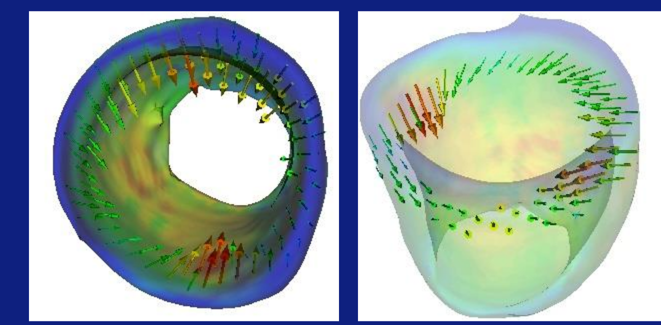

Figure 3: MR Cardiac atlas with motion vectors.

Electro-mechanical model and cardiac atlas: A forward 3D **electro-mechanical model** of the heart [5] was used to validate our activation detection results in a qualitative manner. We also used a **cardiac atlas of geometry and motion** [6] generated from 3D MR images sequences of 14 volunteers to test our activation measure in a realistic but smooth and virtually noise-free data set (Figure 3). The segmentation of the myocardium of the reference subject for the atlas was used as geometric input for the electro-mechanical model. The muscle fibre orientation and the Purkinje network location were fitted to the geometry from a-priori values of the model. Figure 4 compares the isochrones for the atlas computed by both, the electro-mechanical model, and the proposed activation measure derived from the motion field.

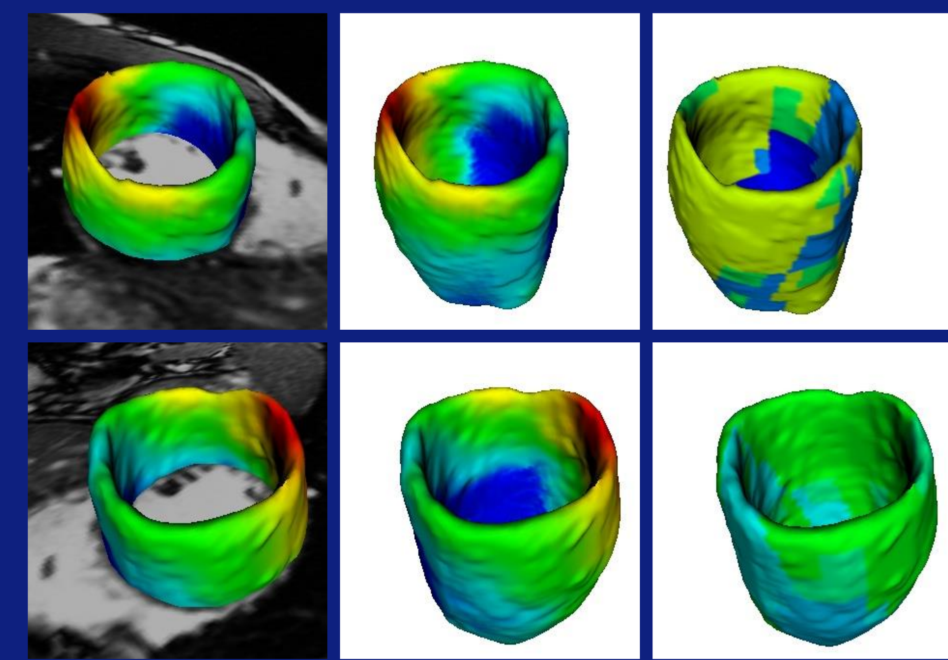

Figure 4: Two views (top and bottom row) of the isochrones were computed for the atlas using both, the electro-mechanical model (first and second column), and the proposed activation measure derived from the motion field (last column). The colour scale goes from blue to red, which correspond to earliest and latest times respectively. The first column shows the orientation of the left and right ventricle on the MR images corresponding to the subject used as a reference for the atlas.

Changes in regional motion patterns: Changes in motion patterns were evaluated on synthetic data as well as real MR data from six subjects.

Synthetic data: In order to test the algorithm when the ground truth is available, results on the 'pre-' and 'post-intervention' sequences of **synthetic** tagged LV images were compared in two cases, with different parameters and regions of abnormal motion (see one case in Figure 2). In both cases these regions were accurately located. One segment showed significant changes while the rest were correctly classified as having no change.

Reproducibility: We also acquired data from four volunteers. For each of them two separate sets of image sequences were acquired with only few minutes between the acquisitions. Since no change is expected in these pairs of image acquisitions, this allowed us to verify the **reproducibility** of the motion fields computed by the algorithm and to test the comparison method against false positive detection. The motion patterns encountered were all very similar and no region was classified as having a significant change.

Stress data: With another volunteer we acquired three sets of image sequences. The first two as described above, with only few minutes between the acquisitions. The third data set was acquired few minutes after the second, but while subjecting the volunteer to **stress**. The stress was induced by placing one foot of the subject into a bucket of cold water with ice. This experiment allowed us to compare normal motion patterns with those obtained under stress, and again, to validate the method regarding reproducibility and false positives. No segment showed a significant difference between the first two acquisitions, but when comparing normal motion to that under stress we found that three segments showed no change, four presented small but noticeable changes, and the remaining five showed a significant amount of change (Figure 6).

Figure 5: XMR system: a combined X-ray and MRI room where operating table slides into scanner.

Ablation patient: MRI data was acquired from an eight year old patient with acute super-ventricular tachyarrhythmia, before and after **RF ablation**. The image acquisition and catheter intervention [1] were carried out with a combined X-ray and MRI room, or XMR system (see Figure 5). Our results confirmed that the motion pattern changed in most parts of the myocardium (visual inspection of the reconstructed 3D surfaces and displacement vectors also showed pronounced changes in the overall contraction pattern), while the largest changes were found in five segments. Examples of the compared motion also show the corrective effect of the intervention (Figure 6).

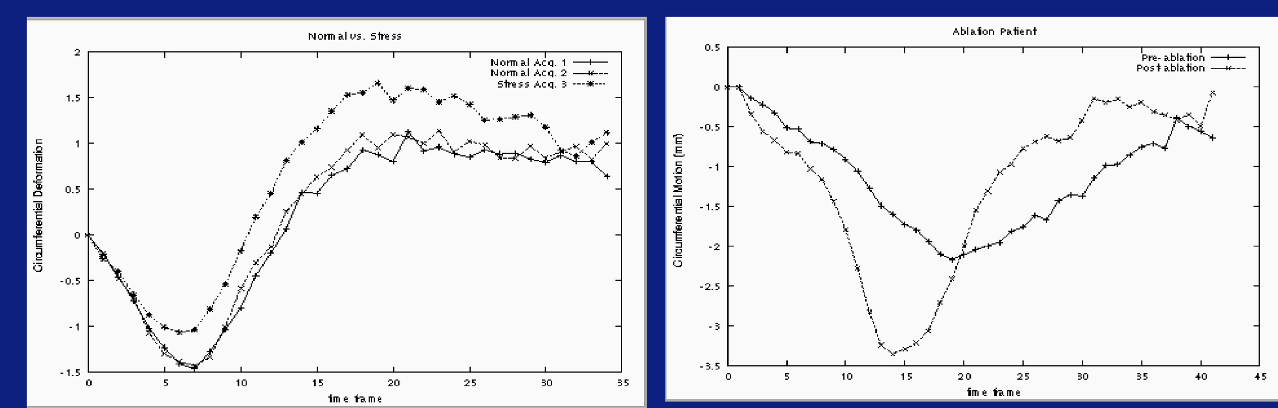

Figure 6: Time plots of circumferential motion of a myocardial segment. (Left) Results for the healthy volunteer show no significant changes in the motion pattern between the first two acquisitions, but a noticeable alteration when **stress** was induced on the subject. (Right) In the case of the patient a significant change can be seen after **RF ablation**, when this region of the myocardium exhibits a faster and more pronounced contraction.

The methodology seems promising for the assessment of intervention results and could also be used for the detection of arrhythmia, infarct, regional dysfunction and follow up studies in general.

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