Localization of abnormal conduction pathways for tachyarrhythmia treatment using tagged MRI

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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. An example of a disease with associated changes in motion patterns are tachyarrhythmias: pathological fast heart rhythm, often the result of abnormal pathways 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, and then treated by applying a RF current via an ablation electrode which induces hyperthermia and destruction of the abnormal pathway. 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. 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 (Figures 1 and 2). 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 compare activation isochrones and regional motion between different image acquisitions, thus assisting in follow up of treatment and particularly in determining whether the ablation 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 (Figure 3). The algorithm aligns 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, modelling cardiac motion using free-form deformations. The output of the registration is a time-varying 3D motion field (Figure 4).

Figure 1: XMR system: a combined X-ray and MRI room where operating table slides into scanner.

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 (aligned with the long-axis of the left ventricle (LV)) introduces a common reference system for comparing motion fields corresponding to different image acquisitions, thus minimising the effect of misregistration due to patient motion during intervention. We also use this coordinate system to subdivide the myocardium into meaningful regions, e.g. 12 segments 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.

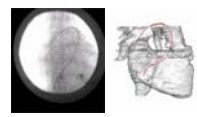

Figure 2: X-Rays and MRI reconstructed cardiac surface aligned for catheter guidance

Motion change and Activation: Displacement, 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 [8], and every region is assigned a time of activation. The isochrones map representation shows these activation times (Figures 7, 8 and 9). Isochrones difference maps highlight changes before and after intervention or fir subjects under stress (Figure 8).

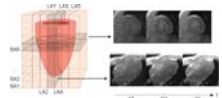

Figure 3: 3D tagged MRI acquisition: Left ventricular short- and long-axis images (cropped images show only regions of interest).

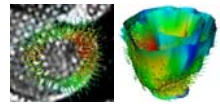

Figure 4: The extracted motion field on a 2D tagged image plane, and on the automatically propagated 3D LV surface (colour scale show motion magnitude, from blue to red).

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 5).

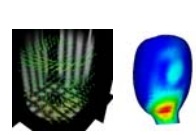

Figure 5: Synthetic cardiac tagged MR images with the extracted motion fields, and the surface with the 'abnormal' motion region identified.

Electro-mechanical model and cardiac MR 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 [7] 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 6). 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 [6].

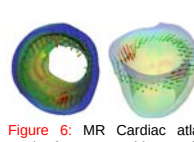

Figure 6: MR Cardiac atlas made from 14 subjects with motion vectors.

Experiments and results

Electro-mechanical model and cardiac atlas: Figure 7 compares the isochrones for the atlas computed by both, the electro-mechanical model, and the proposed activation measure derived from the motion field. Good agreement can be seen between both.

WPW tachyarrhythmia patient: A pre-operative MRI study on a tachyarrhythmia patient with Wolff-Parkinson-White (WPW) syndrome was used to test the methodology in a clinical scenario, predicting the abnormal pathway location before the ablation intervention (Figure 9). The automatically estimated position of the pathway (the earliest activation site) was approx. 5mm away from the estimates of two experts based on visual inspection of a 3D anatomical MRI sequence acquired immediately after the tagged scan, with higher spatial and temporal resolution than the tagged images.

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. In both cases these regions were accurately located (see one case in Figure 5). 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. Motion patterns encountered were all 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 some segments showed noticeable changes (Figures 8 and 10).

Ablation patient: MRI data was also acquired from a patient with acute super-ventricular tachyarrhythmia, before and after RF ablation. The image acquisition and catheter intervention [1] were performed on a XMR system (Figure 1). Results confirmed that motion patterns 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 10).

Conclusions

Methodology uses MRI to provide pre- and intra-operative guidance, locating regions with abnormal motion and activation patterns. The method compares regional motion and activation patterns, useful also for follow up of treatment. Current limitations are distinguishing between endo- and epi-cardium, and motion tracking of the atria. Future Work will use fibber's orientation, electro-physiological study measurements.

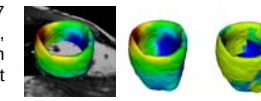

Figure 7: Activation isochrones computed for the MR atlas using both, the electro-mechanical model (centre), and the proposed activation measure derived from the motion field (right). Blue and red correspond to earliest and latest times respectively. The orientation of the left and right ventricle can be seen on a MR image of the subject used as reference for building the atlas (left).

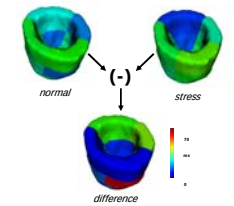

Figure 8: Activation isochrones computed from normal (left) and stress (right) acquisitions, and the difference between the two (bottom). The colour scale for the isochrones difference highlights the regions with most changes. The LV was subdivided in twelve segments.

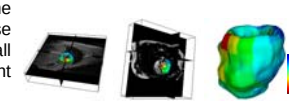

Figure 9: Activation times of tachyarrhythmia in patient with Wolff-Parkinson-White syndrome, derived from the motion field and displayed on the reconstructed LV surface (right). The orientation of the left and right ventricles can be seen on the tagged (left) and anatomical (centre) MR images. In order to highlight the area of earliest motion the colour scale goes from red (earliest) to blue (latest). The LV was subdivided in 120 segments in order to increase the accuracy of the estimated location. The error found with respect to measurements from experts was approx. 5mm.

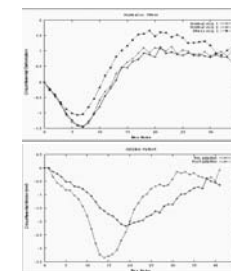

Figure 10: Time plots of circumferential motion of a myocardial segment. Results on healthy volunteer show no significant changes in the motion pattern between the first two acquisitions, but a marked alteration when **stress** was induced on the subject (top). In the case of the patient, pre and post **RF ablation** images exhibit a restored, rapid and pronounced contraction (bottom).

References

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