Mechanical Activation Computation from Fluoroscopy for Guided Cardiac Resynchronization Therapy

Emily Thomas, Daniel Toth, Tanja Kurzendorfer, Kawal Rhode*, and Peter Mountney*

***Abstract*—Congestive heart failure is associated with significant morbidity and mortality, as first line treatments are not always effective in improving symptoms and quality of life. Furthermore, 30-50% of patients who are treated with cardiac resynchronization therapy (CRT), a minimally invasive intervention, do not respond when assessed by objective criteria such as cardiac remodeling. Positioning of the left ventricular lead in the latest activating myocardial region is associated with the best outcome. Cardiac magnetic resonance (CMR) imaging can detect scar tissue and interventricular dyssynchrony; improving the outcome of CRT. However, MR is currently not standard modality for CRT due to its cost and limited availability. This paper explores a novel method to exploit interventional X-ray fluoroscopy set up in CRT procedures to gain information on mechanical activation of the myocardium by tracking the movement of vessels overlying to left ventricular myocardium. Fluoroscopic images were labelled, to track branch movement and determine the motion along the main principal component associated with cardiac motion, to optimize lead placement in CRT. A comparison between MR- and fluoroscopy-derived mechanical activation was performed on 9 datasets, showing more than 66% agreement in 8 cases.**

I. Introduction

Cardiovascular disease (CVD) is the leading cause of death and affects populations worldwide, contributing to 42% of deaths in the EU [1]. In the UK, the burden of CVD on the economy in 2011 was predicted to be £30 billion; 60% was due to healthcare costs [2]. Congestive heart failure with dyssynchrony results in reduced function of the left ventricle as electrical impulses are delayed in transmission to the ventricles [3]. First line pharmacological interventions are not always effective in improving symptoms and quality of life. Cardiac resynchronization therapy (CRT) is proven to reduce mortality in patients with chronic systolic heart failure and ventricular dyssynchrony. This minimally invasive intervention can alleviate symptoms: increase ejection fraction and shorten QRS [4]. Despite this, CRT has a high non-response rate associated with sub optimal left ventricular (LV) lead placement [5]. The presence of scar tissue in the position of the lead hinders the activation of the myocardium. Recent developments in cardiac magnetic resonance (CMR) imaging have improved the detection of scar and inter-/intraventricular dyssynchrony. Using these techniques has shown that positioning of the LV lead in the latest activating region of myocardium is associated with the best outcome of CRT. However, this technique is an additional cost and not available in clinical settings. Other modalities have been used to compute the mechanical activation. Research has shown that it is feasible to calculate the latest mechanically activating segment from computed tomography (CT) for optimal lead position, despite the radiation risks associated with patient exposure [6]. Ultrasound speckle-tracking 2D radial strain imaging can be used to detect dyssynchrony in addition to identifying the latest activating segment. However, the accuracy of ultrasound is user dependent [7].

This paper presents a novel method, which estimates mechanical activation information by tracking vessels motion in venograms. The approach does not require additional pre-operative imaging and enable guided CRT lead placement using only intra-operative imaging. It is validated on 9 cases where ground truth activation is acquired from MRI (magnetic resonance imaging).

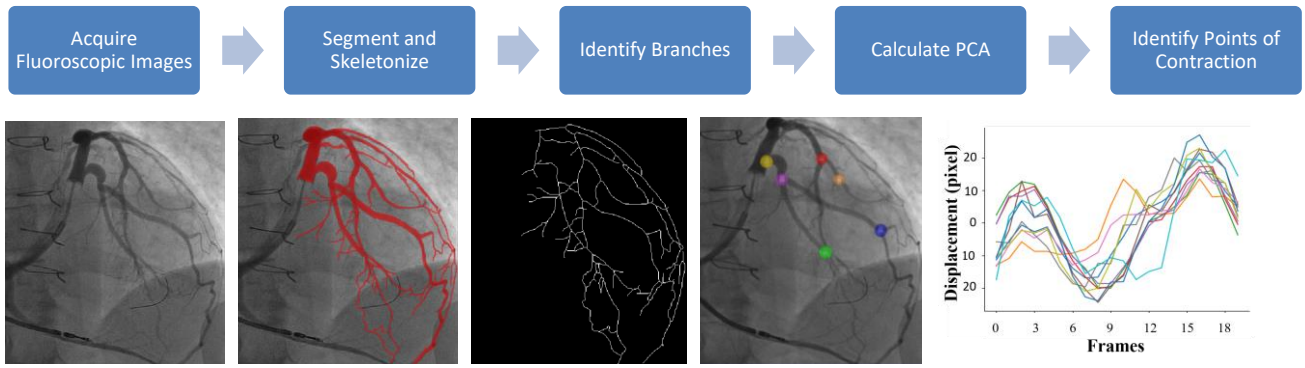

Figure 1: Workflow of Mechanical Activation computation using fluoroscopic images

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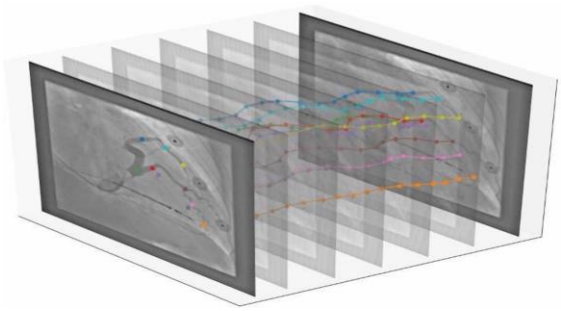


Figure 2: Tracking bifications through the cardiac cycle. The lines represent the movement of the labels over time.

II. METHODS

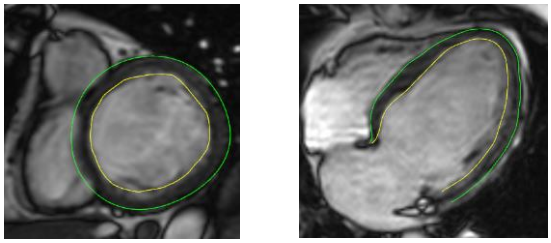
A. Overview

In this work, venograms acquired during the CRT procedure are used to derive mechanical activation and identify the latest activating region of the LV. For a schematic overview of the proposed workflow see Fig. 1. Each patient's coronary anatomy was segmented from the venograms. These segmentations were then skeletonized and the branches of the coronary sinus (CS) were identified and tracked. Mechanical activation was derived from the tracked points by analyzing their motion, see Fig. 2. Mechanical activation curves were computed for each branch to identify the latest activating vessel to place the LV lead in.

B. Mechanical Activation from X-ray fluoroscopy

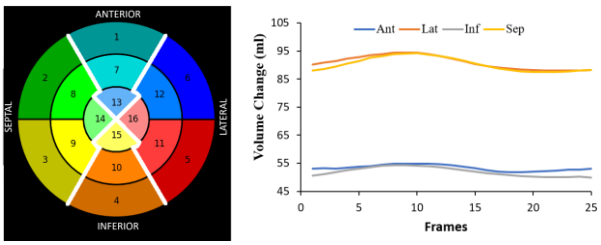
To compute the mechanical activation curves derived from X-ray images each patient required a contrast enhanced fluoroscopy. As the coronary veins overlie the epicardium the latest moving vessel will correlate to the latest activating segment of the myocardium. The coronary veins were manually segmented to track their movement. The resulting segmentation mask was skeletonized to clearly show the branches occurring from the main vein of the coronary veins, the CS. Each of the branches are manually labelled and numbered that each branch could be tracked throughout the frames of the cardiac cycle captured by fluoroscopy.

Principal component analysis (PCA) was performed to calculate the characteristic axes of motion of the labelled branches in 2D [8]. The main principal component is associated with cardiac motion. The motion of the labelled branches is projected onto the axis corresponding to the main principal component. This motion is visualized throughout the cardiac cycle and the points of contraction were located by assessing the timing of the minima of each calculated motion



a) b)

Figure 3: Segmentation of the epicardial (green) and endocardial (yellow) borders, a) shows the short axis slice, b) illustrates a 4-chamber long axis slice.



a) b)

Figure 4: Mechanical Activation computation from MR. a) displays the four regions summed from the 16-segment bullseye plot, b) displays an example of the summed Mechanical Activation curves from Case 1.

curve. Looking at these features it was possible to estimate the mechanism of contraction for each label and any delay between labels was noted suggesting dyssynchrony.

An alternative method to compute mechanical activation from X-ray fluoroscopy is to measure the relative position of two labelled branches throughout the cardiac cycle. However, strain measurements can mistake normal or synchronous contraction of the myocardium as akinetic when two labels are close together. Temporal resolution cannot distinguish between the two different events.

III. RESULTS

A. Validation

CMR was used to validate the mechanical activation estimated using the proposed approach. Each patient required a multi-slice cine steady state free precession (SSFP) scan.

The short and long axis images were segmented automatically, to extract the endocardial and epicardial borders, see Fig. 3. The segmentation was performed by a statistical shape model-based algorithm [9]. Manual spatial contour re-positioning enabled the correction of the misaligned borders which was performed, if necessary.

With the help of the principal axis of the model, a personalized 16-segment 3D epicardial shell for each patient was computed. The segments were accumulated into four regions: Anterior, Lateral, Inferior, and Septal to average disturbing variations between the segments that may have occurred during computation of the curves, see Fig. 4. The volume within each of these regions was calculated using the principal axis, the area and the slice spacing. The change in volume within these regions was tracked throughout the cardiac cycle, to derive the mechanical activation of the regions.

To establish the correspondence between venous branches and myocardial regions, the tracked branches were reconstructed in 3D to verify which region the branch was situated in; to compare the mechanical activation curves from the two modalities [10].

B. Data Description

To compare the mechanical activation curves derived from each modality, each patient required a contrast enhanced fluoroscopy scan and a multi-slice cine SSFP MR scan. Eight patients had sufficient quality in both X-ray images and CMR data. From the eight patients studied, 9 cases were created; one patient had fluoroscopic images acquired in two orientations.

X-ray Fluoroscopy: Fluoroscopic sequences were acquired with the whole heart and its movement for at least one cardiac cycle so that a successful segmentation and annotation of the scan could be achieved. Either 7.5 or 15 frames per second (fps) scans were acquired with a temporal resolution of 133ms and 67ms respectively. The angulation was either anterior posterior (AP) or right anterior oblique (RAO30).

MR: The temporal resolution of each scan was dependent on the patient's heart rate; the temporal resolution varied from 23-43ms. The slice spacing for each case remained at 10mm with pixel spacing varying from 1.302-1.822 mm.

C. Cardiac motion analysis

As previously described in Section II.B, PCA is used to characterize cardiac motion. An example of derived curves that clearly display the cardiac cycles is Case 1, illustrated in Fig. 5. The slow increase between the second and third contraction is due to respiratory motion which influences PCA. The minima or maxima of these labels are compared and some cases show that some labels activate later than others, see Fig. 6.

To compare the mechanical activation curves from different modalities is challenging, due to the different temporal resolutions. Therefore, some volume changes that are demonstrated on MR mechanical activation will not be shown on the fluoroscopy scan. Furthermore, the temporal resolution of the CMR scan will vary with each patient depending on the heart rate or nominal interval (average cardiac cycle length in MR).

There were 9 cases that were analyzed in this work. Altogether 44 branches were tracked and PCA curves were computed. Each label was reconstructed in 3D to be assigned a region and therefore a mechanical activation curve to compare with the PCA curves. Calculating the temporal resolution of the two modalities allows the comparison of the labels to the first label in each case. The first label became the reference label for all the following labels in each case which describes the timing of each label.

Agreement between MR and X-ray was defined as any delay of a label seen in both modalities. Furthermore, if delay was seen in X-ray then some delay should be seen in MR due to the higher temporal resolution. The percentage of labels that showed agreement between the modalities was calculated for each case, see Tab. 1.

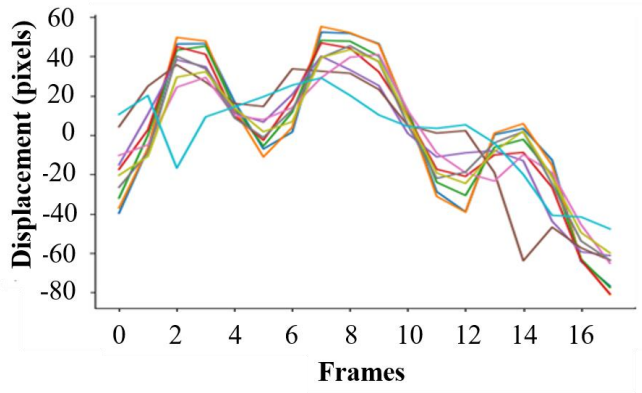


Figure 5: Case 1 PCA results. This case displays 3 cardiac cycles contracting in synchrony.

D. Potential in Clinical Setting

Case 7 illustrates CMR derived mechanical activation curves of regions that activate later than others and therefore optimal for lead placement for CRT. This is represented by some labels are delayed to the reference label. These regional mechanical activation curves are compared to the labels that are reconstructed into these regions. A delay in activation was illustrated between labels 3 and 6 from labels 5 and 8, see Fig. 6 a). This trend is also seen in the summed CMR Anterior and Lateral mechanical activation curves that the labels are reconstructed into, see Fig. 6 b).

Although the length of the delay between the 2 sets of labels were different between the modalities there was agreement between the order of the labels activating. These results are in keeping with the proposal of using fluoroscopic images to assess the optimal placing site of the LV lead in CRT.

E. Overall Results

From the 9 cases that were analyzed 2 cases show 100% agreement on the delays computed from both CMR and X-ray mechanical activation curves. With 8 out of the 9 cases having over 66% agreement between the delays to the reference label, see Tab. 1.

This novel method has the potential to exploit current protocols of CRT delivery to improve the outcome of the procedure. One limitation of this method of tracking coronary vein movement is also affected by respiratory motion that occurs within the thorax. In some cases, this motion dominates which is reflected when PCA is performed seen in Case 4, see Fig.7. In this case the arch-like curves of labels 3, 4, 5, and 6 are clearly different from the cardiac cycles that are present in labels 2 and 7. The respiratory motion is in keeping with the diaphragmatic movement hence the slow change in gradient of the curves.

PCA of the cardiac motion has a steep gradient from the rapid change of volume in the cardiac chambers during systole. As the curves of the labels no longer analyze cardiac motion they are excluded from the validation with CMR in this study. The patient number in the evaluation presented in this will be expanded, to prove usefulness in a clinical setting. However, the difficulty lies in acquiring X-ray fluoroscopy of reasonable quality and CMR images from the same patient.

TABLE 1: QUALITATIVE AND QUANTITATIVE RESULTS

Case	Total Agreement	Label Agreement (%)	+66% of labels agree
1	Yes	100	Yes
2	No	80	Yes
3	No	67	Yes
4	No	67	Yes
5	No	25	No
6	No	83	Yes
7	No	83	Yes
8	Yes	100	Yes
9	No	71	Yes

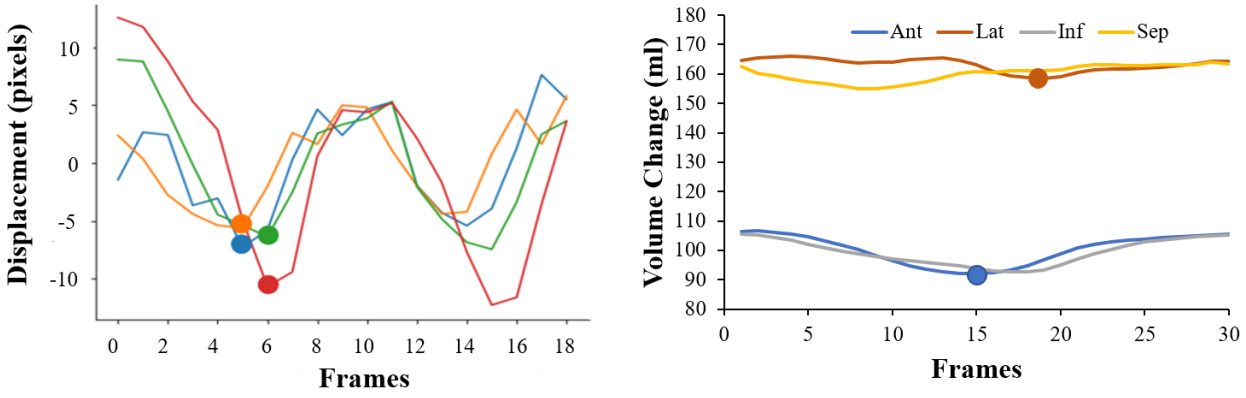


Figure 6: Case 7 Results. a) PCA results, labels 3, 5, 6, and 8 (blue, orange, green, red) minima or maxima are highlighted with color-coded dots. b) Mechanical Activation curves derived from CMR data for Case 7, labels 3 and 5 were reconstructed into the Anterior (blue) curve which activates earlier than labels 6 and 8 in both modalities.

IV. Conclusion

This work presents a novel method to extract mechanical activation of the left ventricle from contrasted X-ray fluoroscopy. The method consists of manual segmentation of the coronary veins, annotating the branches of the veins, tracking the 2D positions of the annotated branches throughout the fluoroscopy sequence, computing the principal components of the motion of the labels, projecting the motion to the axis corresponding to the first principal component and analyzing the resulting motion curves. The motion is associated with the motion of the cardiac wall. The minima, that define the points of contraction, are identified and their relative delay is measured. The latest minimum identifies the vessel to be targeted during CRT delivery. The method was evaluated on 9 cases (8 patients) by comparing against mechanical activation computed from MRI data. The X-ray results are in good agreement with the MRI derived values. The agreement was above 66 % in 8 out of 9 cases and even 100 % of labels agreed in 2 cases. These initial results suggest that the method could enhance guidance of conventional CRT interventions, without the use of preoperative information.

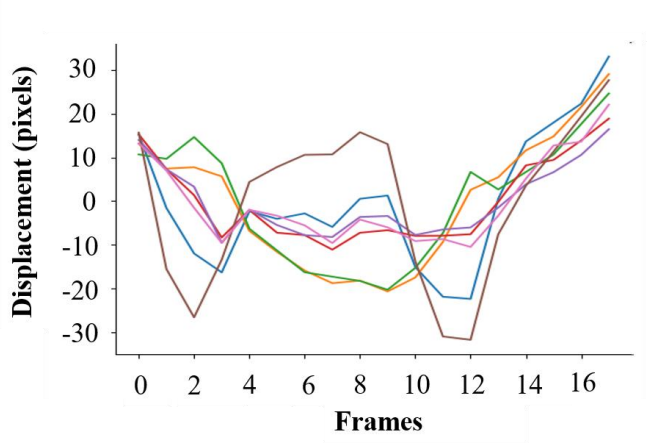


Figure 7:PCA results from case 4. Label 2 and 7 represent cardiac motion whilst the other curves are dominated by respiratory motion.

Acknowledgments and Disclaimer

Concepts and information presented are based on research and are not commercially available. Due to regulatory reasons, the future availability cannot be guaranteed. This work was supported by the Wellcome EPSRC Center for Medical Engineering at KCL (WT 203148/Z/16/Z). The experimental procedures involving human subjects described in this paper were approved by the institutional review board.

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