MRI to X-ray Fluoroscopy Overlay for Guidance of Cardiac Resynchronization Therapy Procedures

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Abstract

Cardiac resynchronization therapy (CRT) can be an effective procedure for patients with heart failure but 30% of patients do not respond. This may be partially caused by the sub-optimal placement of the left ventricular lead. We demonstrate how pre-procedural cardiac MR images can be used to assist CRT by integration of anatomical and functional information with live X-ray images. We evaluated our approach in 7 patients. Each patient underwent pre-CRT MRI scan using MultiHance contrast. This included whole heart imaging sequence; 3D tagged and cine imaging for function; and late enhancement imaging for scar. The MRI data were processed to yield a detailed anatomical model. Whole heart segmentation was achieved automatically using the Philips EP Planner and the coronary venous anatomy was manually segmented by a clinical expert. Functional information was derived using the Tomtec 4D LV-Analysis. The left ventricle was segmented into the standard 16 segment AHA model and the functional information could be added to this. If scar was present, this was segmented by an expert and added to the model. The implant was carried out using a Philips Allura X-ray system and the detailed cardiac model was registered to the X-ray fluoroscopy using multiple views of a catheter looped in the right atrium. There was complete freedom of movement of the X-ray system and respiratory motion compensation was achieved by tracking the diaphragm. The software framework was a specially modified version of the Philips EP Navigator. We validated the registration using balloon occlusion coronary veno-grams. The mean 2D target registration error for 7 patients was 1.3±0.68 mm. Furthermore, left lead deployment was successful in all patients.

1. Introduction

Cardiac resynchronization therapy (CRT) can be an effective procedure for patients with heart failure but more than 30% of patients do not respond. X-ray imaging alone is used to guide placement of pacemaker leads for CRT, but this modality provides little functional or anatomical information to the cardiologist. Lead placement is performed by steering relatively "blindly" which contributes to procedural failure rates of 5 to 12%. Furthermore, leads placed in sub-optimal positions may contribute to the high non-response rate. Previous work with overlay technology has demonstrated that fusion of computed tomography and fluoroscopy may support electrophysiologists in more accurate delivery of therapy during atrial fibrillation ablation [1]. Recent examples [2, 3] have demonstrated that a similar overlay approach using magnetic resonance imaging (MRI) fused to X-ray fluoroscopy is a powerful combination for CRT procedure guidance. MRI offers unique soft tissue contrast without the use of ionizing radiation for depicting coronary vein morphology, quantifying myocardial dyssynchrony, and identifying scar tissue. It is widely believed that these elements are key determinants of clinical outcomes for CRT and that they should be used for patient selection, procedural planning, and guidance.

Cardiac magnetic resonance (CMR) imaging provides a potential complete imaging solution for CRT patients. Whole heart MRI can provide knowledge of the anatomy of the coronary veins which is increasingly important in CRT. Failure to implant a left ventricular (LV) lead is often due to inability to cannulate the coronary sinus (CS) or unfavorable venous anatomy resulting in the inability to find a stable lead position [4]. In addition, the whole heart MRI data can be processed with automatic segmentation tools to produce patient-specific ventricular and atrial anatomical models [5]. The combination of the chamber and coronary venous models can then be used as a 3D roadmap for procedure guidance. Furthermore, cine MRI can provide information about the motion of the LV. Automatic motion analysis software, such as the TomTec 4D LV Analysis tool (TomTec Imaging Systems, Munich, Germany), can give information about the latest activating regions, thought to be important targets for lead delivery. This functional information is often provided to the cardiologist using the standard 16 segment American Heart Association (AHA) model of the LV. CMR also

allows assessment of myocardial scar using late Gadolinium enhancement. It is known that positioning an LV lead within areas of scar reduces response to CRT. Segmenting and registering the position and extent of myocardial scar and overlaying this information on to X-ray fluoroscopy could assist the cardiologist during the implant to avoid these areas.

In this paper, a complete software/workflow solution for the guidance of CRT by using pre-procedural MRI data combined with live X-ray fluoroscopy is presented. The proposed workflow solution explores all the ideas described above and has been tested on 7 clinical CRT cases.

2. Methods

All patients fulfilled the criteria for CRT. Prior to their implants, they all underwent CMR (Philips 1.5T Achieva, Phillips Healthcare, Best, The Netherlands)). All image-guided CRT procedures were performed using a single plane flat-panel cardiac X-ray system (Philips Allura Xper FD10) in the catheterization laboratory by a single experienced operator.

2.1. MR imaging and anatomical model generation

For all patients both respiratory- and cardiac-gated CMR images were acquired prior to the implant on a Philips Achieva 1.5T MR system. Cardiac synchronization was performed with vector electrocardiography (VECG). After localization and coil sensitivity reference scans, an interactive real-time scan was performed to determine the geometry of the short axis (SA), four (4CH), three (3CH) and two chamber (2CH) views. A multiple slice (M2D) cine steady state free precession (SSFP) scan was performed in SA orientation to assess the ventricular function (FA=60°, TR/TE=2.9/1.5ms, resolution 2.2x2.2x10mm, 30 heart phases). Visual assessment of the 3Ch view (FA=60°, TR/TE=3.0/1.5ms, 60 heart phases) was used to determine end systole. For contrast enhanced MRI of the coronary veins, dimeglumine-gadobenate (Gd-BOPTA) (Bracco Imaging SpA, Milan, Italy) was infused with subsequent saline flushing as proposed by Bi et al. [6] for coronary arteries. In order to determine the optimal start point of the whole heart coronary vein MR-scan, a dynamic ECG-triggered 2D-scan with inversion recovery (IR) preparation (TI=300ms) was used. For coronary vein visualization, an ECG-triggered respiratory navigated 3D IR-SSFP MR-scan was applied to acquire the whole-heart during a short interval (60-80ms) in end-systole using the following parameters: FA=50°, TI=300ms, TR/TE=4.25/1.44ms, resolution was 1.5 x 1.5 x 2mm (contiguous slices). A SA stack of late Gadolinium enhancement imaging was performed after the 3D whole heart imaging.

The endocardial surfaces of the right ventricle, left atrium and right atrium and the epicardial surface of the LV were extracted automatically by using a model-based segmentation algorithm [5] from the 3D IR-SSFP whole heart image data. The reason for using the epicardial surface of the LV is that the implanted left lead is placed on the epicardial surface through the coronary veins. All segmentations allowed for manual adjustments when required. In addition, the CS was manually segmented from whole heart image data by a clinical expert to yield a highly detailed anatomical model, which included the CS main branch and three sub-branches.

2.2. LV motion analysis

TomTec 4D LV Analysis is a software solution to analyze and visualize LV function and LV dyssynchrony in cardiac cine MR image data. As shown in figure 1A, the LV surface has been divided into 16 segments according to the definition of the AHA model. Based on regional volume, 16 mechanical delay motion curves are generated (figure 1B). Prior to the CRT procedure, the cardiologist chooses the segment which has the latest activation according to the motion analysis. As the TomTec software does not support export of the 16 segment model, functionality to generate the AHA model from the MR image data was added to the guidance software solution and the latest activating segment was marked.

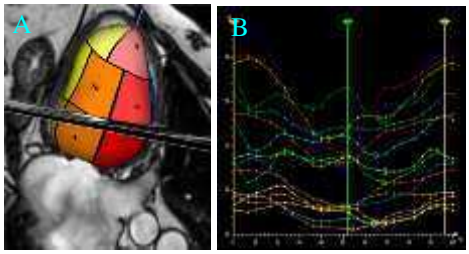

Fig. 1. (A) 16 segment AHA model generated from whole heart MR image data. (B) 4D LV mechanical delay motion curves.

2.3. Scar processing

In patients with myocardial scarring, the position and extent was determined from the late Gadolinium enhanced MR images. These image data were registered to the whole heart MRI data. The scar information could be transferred to the anatomical models in 2 ways: firstly, the 3D myocardial scar could be manually segmented by a clinical expert using ITK-SNAP [7]. The scar would then be visualized as a 3D entity as part of the anatomical model; secondly, a more automated approach could be

taken as described in [8]. In this approach, the scar information is projected on to the LV epicardial surface using a maximum intensity projection. This data is then binarised to give a regional distribution of scar on the LV epicardial surface (figure 2). Both methods were used and the cardiologist was able to select either type of visualisation during the implant.

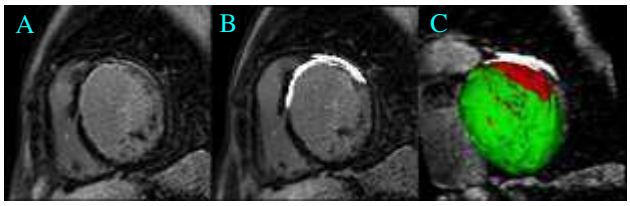

Fig. 2. (A) Original MR late Gadolinium enhancement image. (B) Manual segmentation of myocardial scar. Scar tissue is labeled in white. (C) The 3D scar was presented as a binary map on the LV surface. Scar tissue is labeled in red on the LV surface.

2.4. Fluoroscopy overlay

An overlay platform was developed based on the Philips EP Navigator environment and as an extension to our guidance system for cardiac electrophysiology procedures [9]. This platform allows for the manual registration of pre-procedural anatomical data to live X-ray images. For each patient, the anatomical model was imported and overlaid on to the live X-ray images to guide the procedure. The registration of the MRI and the X-ray data was achieved using multiple views (at least 3) of a catheter looped in the right atrium as a feature for manual registration (figure 3A), taking less than 5 minutes. As the guidance platform received the live X-ray stream from the Philips Allura X-ray system and the positions of the C-arm and X-ray table during the implant procedure, alignment between the anatomical model and the live X-ray images was automatically maintained throughout the procedure as long as the patient did not move on the X-ray table. To compensate respiratory motion in real-time, the left or right hemi-diaphragm was tracked in the 2D X-ray images using mean squared difference between a current image and a reference image within a pre-defined region of interest. The 1D translation along the long axis of the region of interest was calculated. A simple translational model similar to the one commonly employed in MRI image acquisition [10] was used to apply the 1D displacement of diaphragm to the 3D anatomical roadmap. The 1D motion correlation factor between diaphragm and heart was 0.6. The 3D heart roadmap was translated along the head to foot vector of the patient.

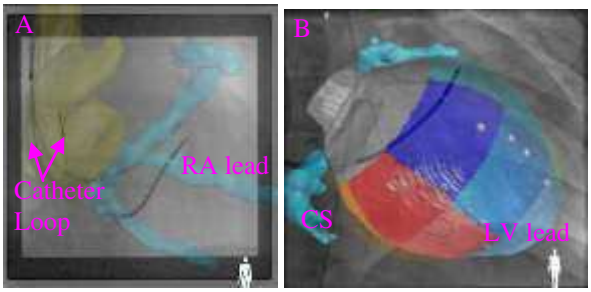

Fig. 3. (A) Using a catheter loop to register the 3D anatomical model with the X-ray fluoroscopic images. (B) Using the 16 segment AHA model to show latest activating region. Grey spheres are the 3D LV lead positions (current and previous), which have been projected to the LV surface.

2.5. Validation of 2D-3D registration

During the procedures, several screenshots of the guidance platform software were taken when venography was performed with an occlusion balloon catheter (figure 4A, 4B). Those screenshots were used to evaluate the accuracy of registration between the 3D anatomical models and the live X-ray fluoroscopy. The distance errors between the centre line of the main branch of the CS in the 3D anatomical models and the occlusive venogram in the 2D X-ray images were calculated (figure 4B). The centre line of main branch of CS was determined from the venogram as well as a centre line for the overlay in a fluoroscopic overlay. The error was defined as the root mean squared distance error between 10 points on the centre line of CS overlay geometry and the 10 nearest points on the centre line of the CS venogram.

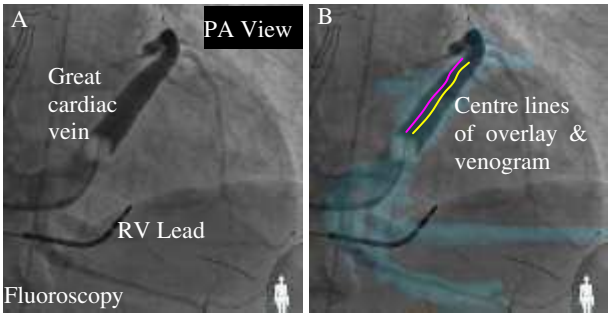

Fig. 4. (A) shows an occlusive venogram. (B) shows how the overlaid coronary veins appeared to the operator during an implant. (C) shows the overlay of the 3D CS segmentation from the CMR data with a centre line for both the venogram and the CS. This was used to determine the registration error.

3. Results

For all 7 patients, the CMR data was of sufficient

quality to allow the generation of clinically useable anatomical models of the cardiac chambers and the coronary venous system. Scar information was added when present and the models were registered successfully to the X-ray fluoroscopic data is all 7 cases during the implantation procedure. The mean distance error between the centre lines of the CS on the overlays and the venograms was 1.3 ± 0.68mm, showing accurate registration with low variability. The guidance platform was used to guide the pacemaker lead positioning and all patients had successful CS cannulation and left lead deployment.

4. Discussion and conclusions

The overlay guidance platform for CRT procedures described in this paper allows the real-time visualization of the cardiac chamber & coronary vein morphology, myocardial scar distribution, and functional information overlaid onto X-ray fluoroscopy to guide the implanter. It can achieve high 2D-3D registration accuracy and facilitated successful LV lead implants in all 7 of the patients in this study. It was of particular help in a patient with a persistent left-sided superior vena cava in which balloon occlusion CS angiography was not possible due to CS dilatation. In this case, the overlay guidance platform offered a potentially unique method of displaying the branches of the CS to guide LV lead implantation. Such techniques therefore may offer the potential to reduce procedure time, contrast dose, X-Ray exposure and complication rates, particularly with inexperienced operators. Also, displaying myocardial scars on the LV model as well as motion information may allow more appropriate targeting for the LV lead.

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