A Framework for CT and MR Image Fusion in Cardiac Resynchronization Therapy

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Abstract

A framework for computed tomography (CT) and magnetic resonance (MR) image fusion is proposed for potential application in cardiac resynchronization therapy (CRT).

The MR dataset has been pre-processed compensating for organ motion induced inter-slices misalignment. The geometrical center alignment of CT and MR short axis (SAX) reconstructed 3D volume has been considered as initialization for voxel-based 6 degree of freedom image registration between 3D CT (moving image) and MR SAX (fixed image). The process driven by normalized mutual information cost function featuring multi-resolution two-level approach with gradient descent optimizer was adopted to improve the numerical stability. The retrieved transformation was applied to CT to perform data fusion with LAX and Gd-enhanced MR images.

Fused data was visually inspected and judged reliable for correspondence of cardiac structures. The proposed approach constitutes the pre-processing step for multi-modality visualization of different information: coronary veins anatomy from CT, necrotic tissue from Gd-enhanced MR, dyssynchrony map from SAX and LAX MR.

1. Introduction

The cardiac resynchronization therapy (CRT) is an invasive cardiological treatment that reduces hospitalization and mortality in patients affected by severe ventricular failure diseases. Despite the large adoption, its efficacy is still not confirmed in a significant number of patients, between 20% to 40%, in studied populations [1].

The main reasons for failure are adduced to complications consequent to the biventricular pacemaker implants, and errors in patient recruitment strategy including, for instance, cases of suboptimal lead placement access with respect to the most delayed myocardial region.

Recently, three dimensional echocardiography has been proposed as non-invasive imaging technique for patient screening and follow-up in CRT studies. However, the limiting factors for echo-imaging adoption in daily clinical routine are related to patient-dependent image quality, limited spatial resolution and high inter-operator variability. In order to overcome these limitations, new clinical protocols include Cardiac Computed Tomography (CCT) and Cardiac Magnetic Resonance (CMR) imaging for improved cardiac anatomy and functionality assessment, without geometrical limitations and inter-operator variability [2].

To date, the combined use of CCT and CMR can significantly improve the success rate of CRT, thus providing to clinicians a method to investigate pre-operatively the venous coronary anatomy and to evaluate accurately the ventricular mechanical dyssynchrony.

In this study, we present a framework of tools and procedures for image registration towards the use of fused CCT-CMRI data in CRT patient recruitment. The method feasibility has been verified on one clinical dataset of a patient undergoing CRT treatment.

2. Methods

2.1. Imaging

The image datasets consisting of three-dimensional CCT images belonging to 40-50-60-70-80% of the cardiac cycle (GE, Helthcare, 512x512x399 voxels with spacing of 0.51x0.51x0.4 mm) of a 72 years old man scheduled for CRT were acquired alongside with CMR (1.5 T, GE, Healthcare) short-axis (SAX), 2- and 4-chamber long-axis (LAX) free-precession images (30 frames/cardiac cycle, 512x512x17 voxels with resolution 0.7422x07422 mm, spacing 8 mm, no gap) and considered for the registration framework benchmarking. Moreover, Gadolinium(Gd)-enhanced SAX and LAX CMR datasets were also acquired for scar detection (MDE 275, single frame 50% of cardiac cycle, resolution 1.4844x1.4844, spacing 8 mm, GE,

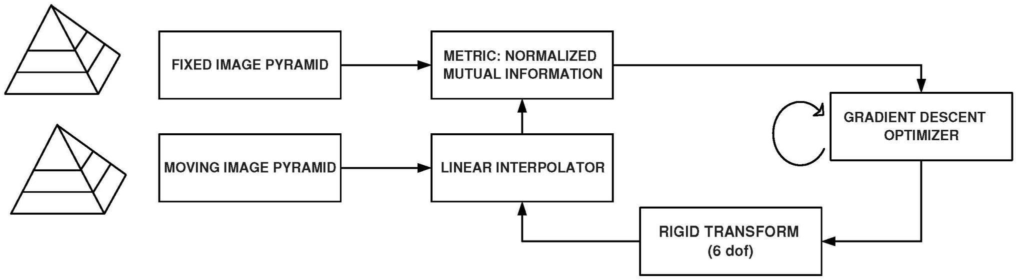

Figure 1. Registration framework

Healthcare, 1.5 T).

The five SAX images stacks corresponding to the same phases of the cardiac cycle as CCT data were selected for intermodal rigid registration.

2.2. CMR pre-processing

The SAX CMR data were pre-processed in order to correct motion-induced inter-slices misalignment in each volume. In fact, the non exact repeatability of the patient apnea during the acquisition potentially introduces movement artifacts in SAX images resulting in relative shifting. To this aim, the SAX images were re-aligned with respect to the 2ch and 4ch LAX planes optimizing the normalized cross-correlation between their intersection planes (see [3] for further details).

2.3. Registration framework

We propose a two step algorithm for CT and MR rigid registration (6 degrees of freedom, dof) for multiresolution inter-modal voxel based 3D to 3D registration driven by normalized mutual information.

Prior to registration, CT and pre-processed CMR SAX datasets were aligned overlying the bounding box centers of their 3D volumes. The resulting translation is provided as initialization to the subsequent optimization function, thus reducing the probability of local maxima solutions convergence.

The ITK registration framework was adopted (Figure 1, [4]) with multiresolution approach chosen for improved numerical stability: two levels of the image pyramid were defined with isotropic subsampling grid equal to [4, 4, 4] and [2, 2, 2]. The finest resolution (i.e. [1, 1, 1] grid) was omitted in order to reduce computational time.

Normalized mutual information (NMI) was chosen as metric to drive the registration, defined as:

$$NMI(A, B) = \frac{H(A) + H(B)}{H(A, B)} \tag{1}$$

where A and B refer to the fixed and moving image, $H(A)$ and $H(B)$ to their associated entropy and $H(A, B)$ to the joint entropy. In particular:

$$\begin{aligned} H(A) &= -\int p_A(a) log p_A(a) \partial a \\ H(B) &= -\int p_B(b) log p_B(b) \partial b \\ H(A, B) &= -\int p_{AB}(a, b) log p_{AB}(a, b) \partial a \partial b \end{aligned} \tag{2}$$

where $p_A(a)$ and $p_B(b)$ are probability densities of A and B, and $p_{AB}(a, b)$ is their joint probability.

NMI derives from information theory and has been widely used in inter-modal voxel based image registration [5–7]. The metric was associated to gradient descent optimizer and linear interpolation. In order to reduce the interpolation workload for improved algorithm performance, the CMR image has been chosen as the fixed image.

The registration process was applied to each CCT frame and its correspondent SAX volume. The algorithm outcomes were qualitatively judged by visual inspection analyzing the correspondence of cardiac structure over the different imaging modalities. The six parameters of the registration process, metric value and computational time are reported for each frame.

The computed transformation allowed to map the CCT frames in the CMR system of reference and thus to integrate CCT with all CMR data. In particular, CCT frame correspondent to 50% of the cardiac cycle was roto-translated in order to match co-registered CMR anatomical and Gd-enhanced data. The obtained data fusion thus allowed a 3D simultaneous visualization of CCT, anatomical and Gd-enhanced LAX and SAX.

3. Results

The first step of the registration, based on the overimposition of the bounding box centers, resulted in translations equal to -36.9, 45.8 and -79.1 mm for the three geometrical axes, respectively. Final registration results are reported in Table 1: mean calculated translations and rotations were equals to -18.1, 44.5, -98.4 mm and -0.079, 0.028, -0.008 rads respectively, requiring less than 10 minutes per frame on a general purpose laptop.

Table 1. Registration results: final translations ($\triangle x_f$, $\triangle y_f$, $\triangle z_f$), rotations ($\triangle\theta$, $\triangle\gamma$, $\triangle\eta$) , NMI value and computational times.

Parameters	frame 1	frame 2	frame 3	frame 4	frame 5
$\triangle x_f$ [mm]	-19.4	-18.1	-18.8	-20.9	-13.5
$\triangle y_f$ [mm]	43.6	44.5	44.2	46.4	43.9
$\triangle z_f$ [mm]	-99.5	-101.3	-98.3	-92.6	-100.2
$\triangle\theta$ [rad]	-0.079	-0.074	-0.079	-0.071	-0.091
$\triangle\gamma$ [rad]	0.031	0.038	0.034	0.035	0.038
$\triangle\eta$ [rad]	-0.007	-0.006	-0.009	-0.013	-0.006
metric value	1.08	1.09	1.08	1.08	1.09
computational time [s]	440	437	434	443	447

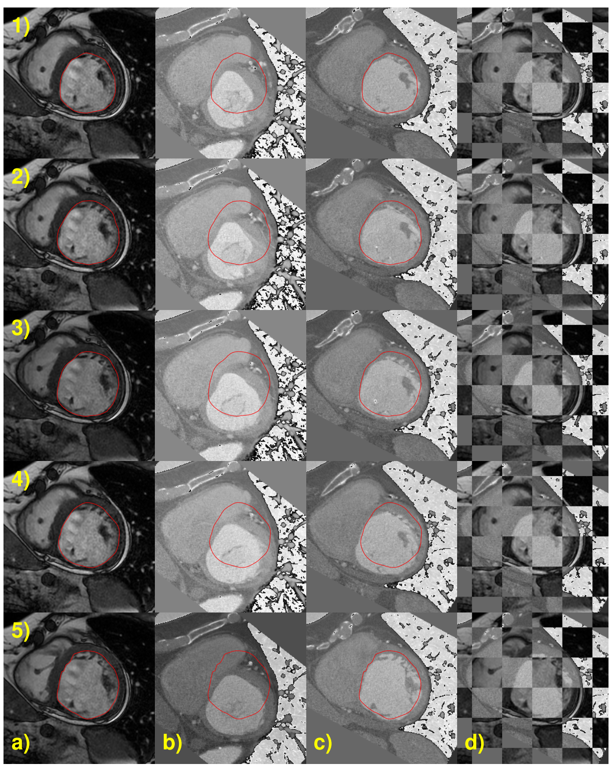

Figure 2. Registration results presented for the 5 frames analyzed (from top to bottom): a) SAX image, b) CT image resampled to the SAX plane after center alignment, c) CT image resampled to the SAX plane after registration, d) checkerboard SAX and registered CT. Endocardial contours traced on SAX plane are superimposed to correspondent CT plane before (b) and after (c) registration process.

The registration was judged qualitatively by visually inspecting the correspondence of cardiac structures in the fused data; as shown in Figure 2 in correspondence of a middle slice SAX CMR and CCT before and after registration. Cardiac structure matching was also evaluated by superimposing endocardial contour on CCT registered data, where the contours were manually defined by selecting seeds for Bezier curve interpolation [8].

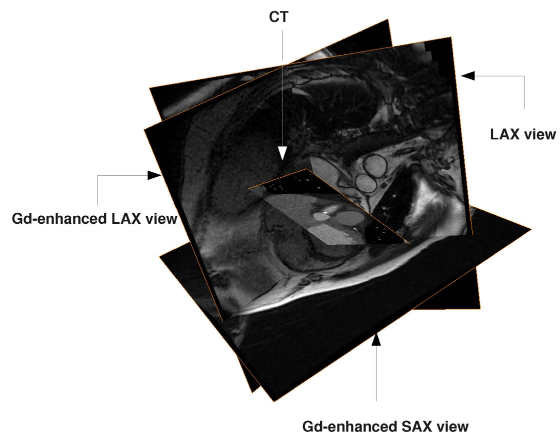

Figure 3. Final transformation between CMR SAX and CCT is applied to CMR LAX and Gd-enhanced SAX and LAX data.

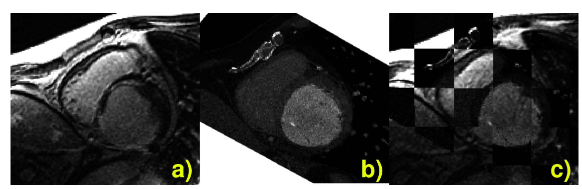

Figure 4. Combined view of: a) Gd-enhanced SAX, b) registered CT and c) checkerboard Gd-enhanced SAX and registered CT

The coordinate transformations were applied to CCT frame correspondent to 50% of cardiac cycle and used anatomical LAX and SAX-LAX Gd-enhanced (co-registered to) with CCT transformed volume; 3D view of registered data is presented in Figure 3 and combined view of CCT and CMR Gd-enhanced by checkerboard technique is shown in Figure 4.

4. Discussion

We presented a framework for CT and CMR datasets automated registration for potential application in CRT patient selection process. The framework was qualitatively evaluated and showed a good matching of correspondent cardiac structures between the different modalities. The pre-processing step aimed at correcting inter-slices misalignment in CMR SAX data, thus minimizing registration errors potentially due to movement artifacts in the images. The reported similar registration parameters for all the considered frames in the cardiac cycle proved the reliability of the calculated rigid transformation. Small differences may be attributed to non perfect temporal correspondence between CMR and CCT frames, as they were acquired with different temporal resolution and in different sessions.

Quantitative validation on a wider population will be the object of future research in order to define a more generic set of registration parameters able to drive the registration process. For this purpose the two step registration will be further investigated, replacing the initial transformation here defined as geometric alignment of bounding box centers by an initial registration performed between CMR axial localizer and CCT volume, as an attempt to increase the algorithm stability.

Potential advantages in the application of this framework stand in the possibility to obtain ventricular function wall motion, thickness, and dyssinchrony parametric maps [9] from the CMR SAX and LAX data, scar position and extension from SAX Gd-enhanced images [10]. Merging this information with CT-derived coronary veins could potentially allow to pre-operatively exclude the scar tissue presence in highest delay heart tissue areas, thus guaranteeing the effectiveness of CRT, and, based on this information, plan the best surgical catheter insertion pathway [11]. Other fields of application of this framework are in the patient-specific modelling of cardiac anatomy [12] and function using information derived from multimodality datasets.

5. Conclusions

The proposed method for registering CMR and CCT data constitutes a pre-processing step for multi-modal visualization, segmentation and modelling of complementary functional, perfusional and anatomical information. The automation of the registration process and its performance, hence evaluated on a single case by visual inspection, suggests its potential applicability in the clinical setting for CRT intervention planning and prediction. Future work will be focused on the quantitative validation of the method in a population of patients recruited for CRT.

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