Multiscale Total Variation Registration for MRI Guided Interventions

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INTRODUCTION: Traditionally, cardiovascular interventions are carried out under X-ray fluoroscopic guidance for diagnosis and treatment of arrhythmias such as atrial fibrillation (AF) and ventricular tachycardia (VT). However, imaging guidance with X-ray fluoroscopy is challenging due to its inherently low soft tissue contrast. Alternatively, the use of MRI to guide cardiac interventions has also been explored via fast real-time (RT) 2D imaging[1,2] or high-resolution 3D prior roadmaps[3]. Unfortunately, there are drawbacks with each of these two approaches. In the case of RT MRI guidance, the image spatial resolution is low, whereas the high-resolution prior roadmaps do not reflect patient respiratory motion during the intervention. In this study, we propose a multiscale image based registration algorithm to correct for subject related motion by registering the prior roadmap to the RT images.

METHODS: Cardiac images were acquired from 8 subjects with a 1.5T MRI scanner (GE Healthcare, Milwaukee, WI). Two separate image acquisition protocols were used. For each subject, a high-resolution scan was performed to acquire a prior roadmap image, followed by a low-resolution real-time scan. The prior roadmap image consists of a multi-slice 3D volume acquisition, which encompassed the heart of the subject. These were acquired in the short axis (SAX) view. The GE FIESTA pulse sequence was used with resolution = 1.36×1.36×8 mm^3, TR/TE = 3.7/1.6 ms, view per segment = 16, flip angle = 45°, FOV = 35 cm. The acquired prior images were gated to end expiration (EE) and mid-diastole. For the RT images, a fast spiral balanced SSFP scan was acquired with in-plane resolution = 2.22×2.22×8 mm^3, TR/TE = 3.65/0.68 ms, flip angle = 45°, and temporal resolution = 65 ms. The RT data were acquired during free breathing and retrospectively gated to mid-diastole.

A multiscale registration framework was implemented to align the 3D prior roadmap image to the 2D RT image. In the proposed approach, both the prior and RT data are decomposed into coarse and fine scale feature images based on the multiscale total variation (TV) flow algorithm[4]. Specifically, we can consider the decomposition of an image f into a smooth component u and a residual component $v = f - u$. To this effect, a multiscale decomposition can generate a multiscale family $\{u_\lambda, v_\lambda\}$, where λ denotes an algorithmic scale parameter. It can be shown that successively smoother images $u(\cdot,t)$ can be obtained via the following:

$$\frac{\partial u}{\partial t} = \frac{1}{2\lambda(t)}\mathrm{div}\left(\frac{\alpha\nabla u(\cdot,t)}{|\nabla u(\cdot,t)|}\right);\quad u:\Omega\times R_+\mapsto R,\quad \left.\frac{\partial u}{\partial n}\right|_\Gamma = 0,\quad u(\cdot, t=0):=f,$$

$$\alpha = \frac{1}{\sqrt{\left(1+|\nabla G_\sigma * f|^2/\beta^2\right)}},$$

where Γ denotes the boundary of the image f and $\lambda(t)$ is a real-valued, monotonically decreasing function. The edge detector function α is computed over a smooth image, obtained via convolution of f with a Gaussian kernel G_σ, and β is chosen such that α attains small values at prominent edges. As time t increases, smoother images $u(\cdot,t)$ containing coarse scale features are obtained. Subsequently, the prior and the RT images are registered using a coarse-to-fine approach via minimizing the normalized gradient field (NGF) distance metric[5] between the images as shown in Fig. 1. Coarse scale features extracted from the prior and RT datasets are registered together first, and the resulting registration parameters are used as the initial guess for the alignment of finer scale features at the next level. This is repeated for $N = 3$ levels.

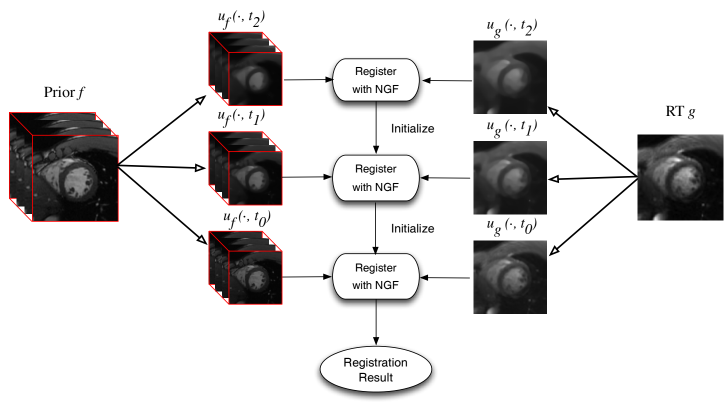

FIG. 1. Multi-scale registration framework. Both the prior *f* and RT *g* images are decomposed into successively smoother images using the multiscale TV flow algorithm. These images are then registered in an iterative coarse-to-fine manner, where the optimal registration parameters from the coarse scale images are used as the initial guess for the finer scale images at the next level.

RESULTS: The registration accuracy was estimated via the Dice similarity coefficient (DSC) and the in-plane target registration error (TRE). The DSC computes the overlap between the manual segmentation masks of the left ventricle (LV) endocardium belonging to the corresponding prior and real-time images respectively. This is demonstrated in Fig. 2, where the overlap between the contours of the LV endocardium masks is shown in Fig. 2b for the initially misaligned case (DSC = 0.829), and in Fig. 2d for the motion corrected case using the proposed registration method (DSC = 0.952). The higher DSC indicates improved image alignment. Subsequently, we performed the DSC analysis for registration of 179 pairs of prior and RT images that were acquired from the 8 subjects (Fig. 3). The average DSC was 0.857 before registration, and 0.952 after registration with the proposed method. For comparison, the mean DSC = 0.945 was also measured for a multiscale registration framework where the coarse-to-fine scale features were extracted using Gaussian filters instead. As a second test, the in-plane TRE measures the distance between observable landmarks (i.e. papillary muscles) from the prior and RT images within the frame of reference of the RT imaging plane. The mean in-plane TRE for the 179 image pairs was measured to be 5.42 mm before registration, and 2.14 mm and 1.84 mm for registrations that used Gaussian filters and the proposed multiscale TV flow technique for feature extraction respectively (Fig. 4).

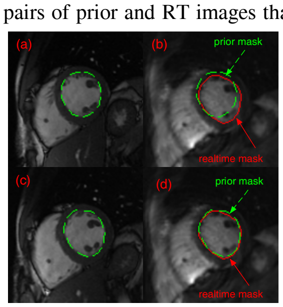

FIG. 2. DSC Measure. (a) Prior image before registration with the corresponding LV mask. (b) Direct overlay of the prior mask is shown with the realtime mask. (c) Registered prior and corresponding LV mask. (d) Overlay of the registered prior mask onto the realtime image.

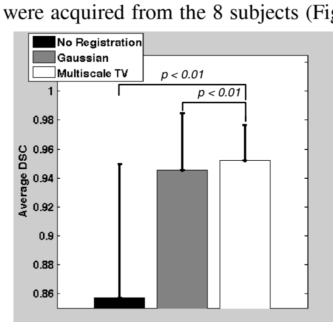

FIG. 3. Average Dice similarity coefficient shown for pre-registration, registration using features extracted from Gaussian filters and the proposed multiscale TV flow algorithm respectively.

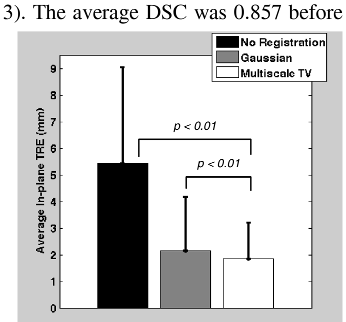

FIG. 4. Average in-plane target registration error shown for pre-registration, registration using features extracted from Gaussian filters and the proposed multiscale TV flow algorithm respectively.

CONCLUSIONS: We have presented an imaging based alignment method that can potentially improve the feasibility of MRI guided cardiac interventions. Specifically, the proposed registration framework can reduce respiratory induced motion errors by registering the static prior roadmap volumes to the dynamically updated real-time interventional images. The proposed method improves the robustness of image registration by extracting different scale features from the original input images and subsequently registering the corresponding scale images in a coarse-to-fine manner. Ongoing work will aim to implement the proposed algorithm using GPU acceleration to facilitate real-time image fusion.

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