Automated Tracking of Deformable Objects Based on Non-Rigid Registration of Cardiac Images

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Abstract

We developed an automated technique for non-rigid image registration as a basis for tracking the heart in contrast-enhanced cardiac magnetic resonance (CMR) image sequences. The goal of the present work was to validate this technique against conventional manual analysis. Our approach is based on a multi-scale extension of the normalized 2D cross-correlation algorithm in combination with level-set methods. This technique was tested on short-axis CMR (Philips 1.5T) image sequences obtained in 11 patients at the mid level of the left ventricle during first pass of a gadolinium bolus. Myocardial identification required around 5s for a 60-frame sequence. To validate the technique, myocardial boundaries were manually traced on all frames by an experienced interpreter. Comparison between automatically registered and manually traced boundaries was performed by computing Hausdorff distance (2.1±1.4px), mean absolute distance (0.9±0.7px), root mean square distance (1.0±0.8px) and Dice coefficient (0.8±0.1). These results indicate that the proposed technique allows fast and accurate non-rigid image registration, and may thus be successfully used for deformable object tracking in cardiac image sequences.

1. Introduction

The extraction of clinically useful quantitative information from cardiac image sequences often relies on the tracking of moving deformable objects, such as cardiac chambers and valves. This task usually requires tedious and time-consuming manual tracing of multiple frames, which is unsuitable for a busy clinical environment. As a result, cardiac image sequences are usually assessed only qualitatively. This is the case for the evaluation of myocardial perfusion from contrast-enhanced CMR images. In fact, the extraction of quantitative information regarding myocardial perfusion requires the identification of the myocardium (i.e. endo- and epicardial boundaries) in multiple consecutive frames. This is usually achieved by manually drawing the myocardial boundaries in one frame and by adjusting their position and shape in the other frames to compensate for cardiac translation and deformation due to in- and out-of-plane respiratory motion [1]. In the last years, research efforts have been made in order to automate this procedure by means of non-rigid registration algorithms. Unfortunately, the development of these automated techniques has been hampered by the high noise levels and low spatial resolution of contrast-enhanced image sequences, together with their extreme dynamic nature and the degree of cardiac translation and deformation due to patient's respiration [2].

We recently developed [3,4] an automated technique for non-rigid image registration as a basis for tracking the heart. This technique adopts a novel multi-scale extension of the normalized 2D cross-correlation algorithm in combination with level-set methods [5]. The goal of the present work was to validate this technique against manual analysis of contrast-enhanced CMR images.

2. Methods

2.1. Population

Eleven subjects (age 56±17 yrs, 7 males) were studied. Exclusion criteria were standard contraindications to CMR imaging with gadolinium DTPA (Gd-DTPA).

2.2. Imaging

Short-axis images were obtained (Achieva, Philips 1.5T scanner) at the mid level of the left ventricle (~60 consecutive end-diastolic frames) using a hybrid gradient echo/echo planar imaging sequence (nonselective 90° saturation pulse followed by a 80 ms delay, voxel size ~ 2.5 x 2.5 mm, slice thickness 10 mm, flip angle 20°, TR = 5.9 ms, TE = 2.7 ms, EPI factor 5, and SENSE factor 2). Imaging was performed during the first pass of a Gd-DTPA (0.075 to 0.10 mmol/kg at 4 to 5 ml/sec). Patients were instructed to hold their breath as long as possible.

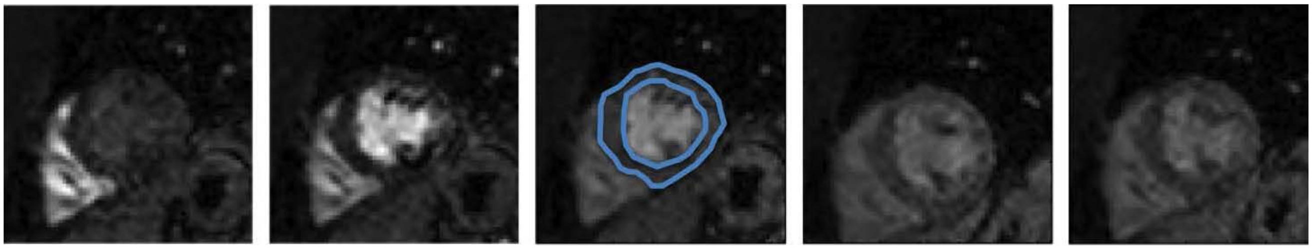

Figure 1. Example of a typical contrast-enhanced CMR image sequence. To initialize the tracking algorithm, the user is asked to select a reference frame and to manually trace the myocardial boundaries on it (middle panel).

2.3. Automated image registration

For each image sequence, for initialization purposes, the operator selects a reference frame and identifies the myocardium by manually tracing the endo- and epicardial contours (figure 1). Non-rigid registration of the traced boundaries onto the other frames of the sequence, which is necessary to compensate for cardiac translation and deformation due to both in- and out-of-plane motion, is achieved by a multi-scale extension of the 2D normalized cross-correlation algorithm in combination with level-set methods. The registration scheme consists of 6 steps (figure 2): 1) an original template is defined as an image crop of the reference frame around the traced boundaries; 2) five additional template images are created by resizing the original template to different degrees (1 pixel difference at a time); 3) 2D normalized cross-correlation is computed between each template and the consecutive frame; 4) the position and size of the myocardial boundaries in the new frame are determined by finding the highest among the six cross-correlation peaks (and thus the size of the corresponding template); 5) both endo- and epicardial contours undergo an edge-based level-set algorithm in order to match the current shape of the myocardium; 6) the templates are updated in the new frame to take into account the changes in pixel intensity due to the passage of contrast (although the shape of the myocardium remains as initially traced). The edge-based level-set technique adopted in step 5 is the Malladi-Sethian model for active contour evolution, including a dependence of the speed on the curvature, a propagation expansion speed and an advection speed based on the image gradient [5]. Using this scheme, the myocardial boundaries are registered onto all the frames of the sequence.

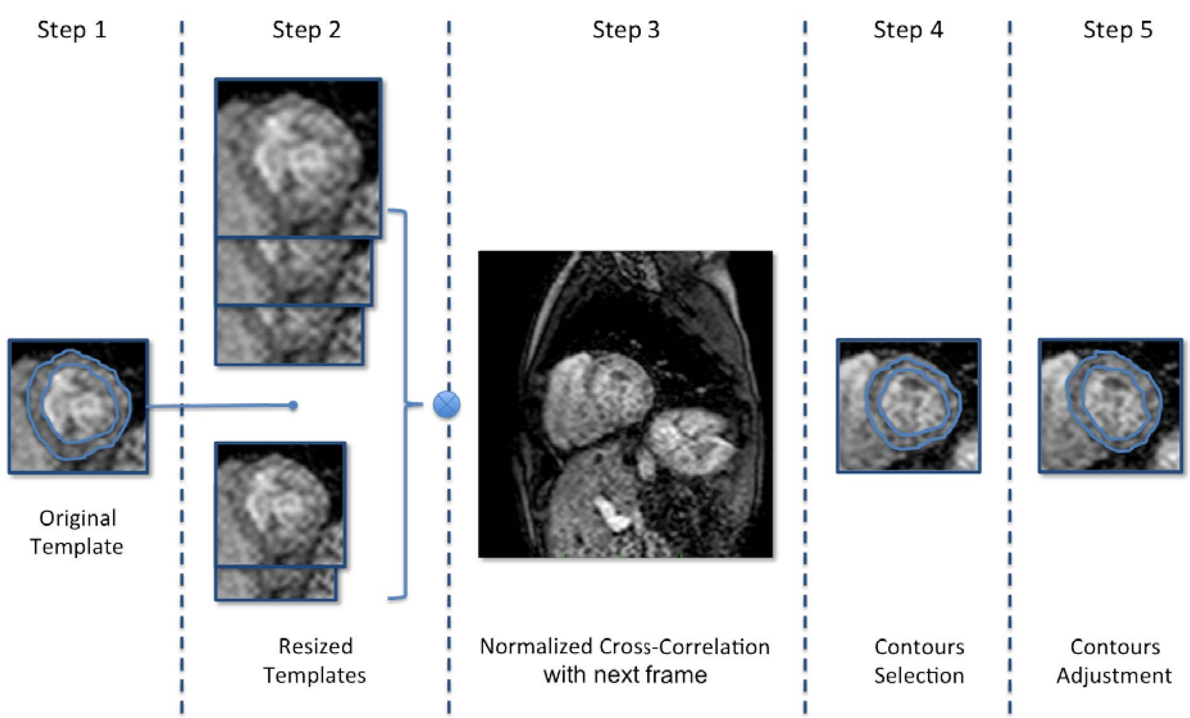

Figure 2. Main steps for the automated non-rigid registration of the traced boundaries between two adjacent frames. Of note, step 6, which consists in template update, is here omitted.

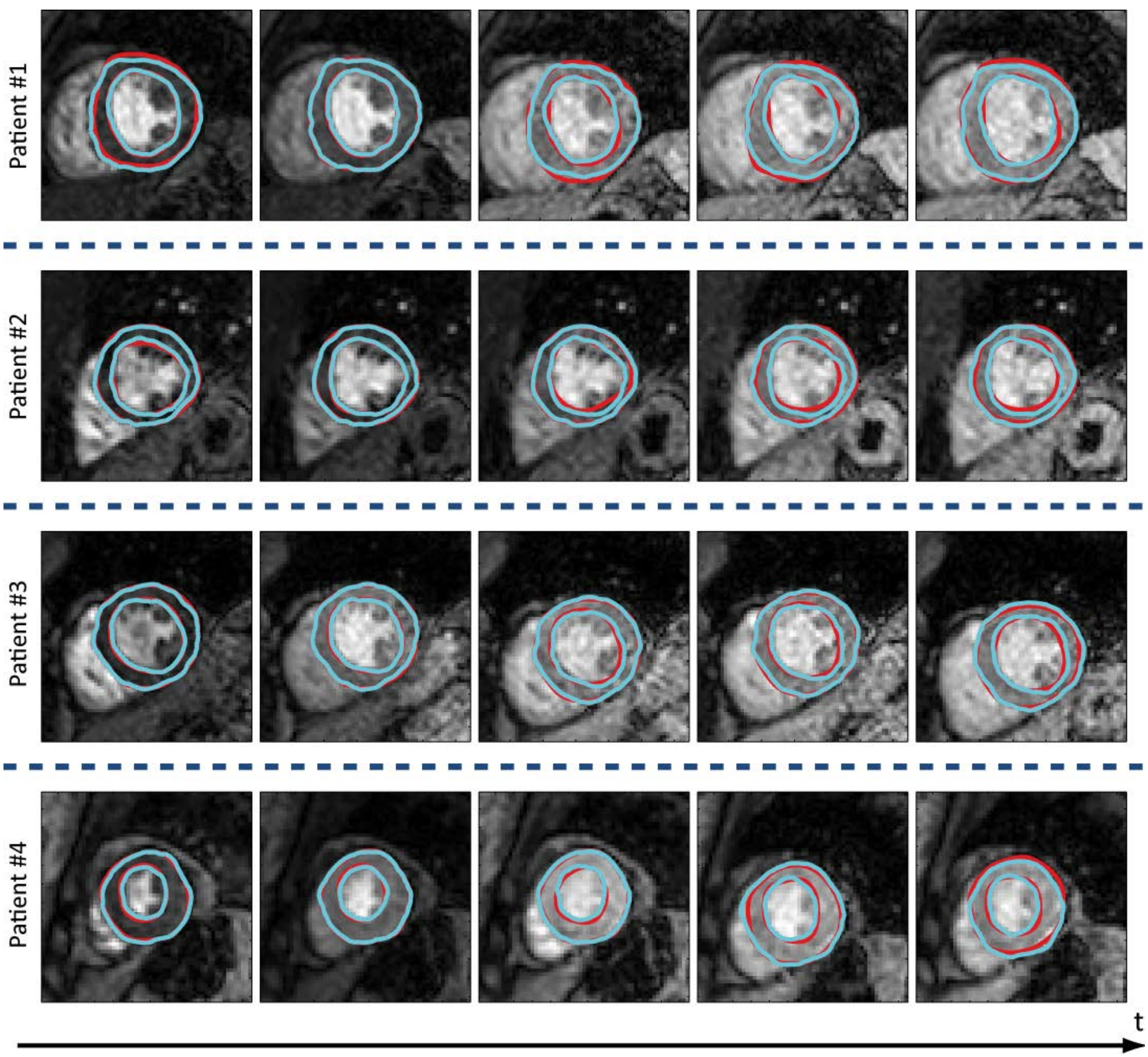

Figure 3. Results of the proposed automated tracking technique in 4 different patients (rows) at different frames (columns). The plotted contours are respectively the automatically adjusted (cyan) and the manually traced (red) contours.

2.4. Performance testing

To validate the proposed registration technique, an experienced interpreter, blinded to the results of the automated analysis, manually traced the endo- and epicardial contours on all frames for every image sequence. To assess the accuracy of the tracking technique, a variety of error metrics were computed between automatically adjusted and manually traced contours. These metrics included the Hausdorff distance (HD), the mean absolute distance (MAD), the root mean square distance (RMSD) and the Dice coefficient (DC) [6]. The first three indices assess respectively the maximum, the mean and the root mean square distance in pixels between the two contours, while the last one represents the normalized size of the overlapping area between them. These error metrics were computed between the automatically and manually identified endocardial contours, the epicardial contours, and both the contours altogether. The resulting values were finally averaged for all the frames of all sequences.

	HD	MAD	RMSD	DC
Endocardial Contour	2.2 ± 1.4	0.9 ± 0.7	1.1 ± 0.8	0.8 ± 0.1
Epicardial Contour	2.0 ± 1.4	0.8 ± 0.7	0.9 ± 0.8	0.9 ± 0.1
Overall	2.1 ± 1.4	0.9 ± 0.7	1.0 ± 0.8	0.8 ± 0.1

Table 1. Results of the comparisons between automatically registered and manually traced endocardial and epicardial contours in all the analysed image sequences by means of several error metrics: Hausdorff distance (HD), mean absolute distance (MAD), root mean square distance (RMSD), Dice coefficient (DC). All the metrics are displayed as (mean ± SD). HD, MAD and RMSD are expressed in pixels, while DC is dimensionless.

3. Results

Time required for the automated registration of a 60-frames perfusion sequence was around 5 s on a standard PC. An example of visual comparisons between the automatically registered contours and the manually traced ones in several frames belonging to different image sequences are displayed in figure 3. The obtained results for the computed error metrics are reported in table 1.

4. Discussion and conclusions

This study was aimed at the validation of a recently developed automated technique for myocardial tracking based on a novel non-rigid registration scheme. The proposed technique consists of a multi-scale extension of the normalized cross-correlation algorithm in combination with level-set methods. The technique was tested on contrast-enhanced CMR image sequences, which are nowadays routinely acquired in the clinical environment to evaluate myocardial perfusion. Unfortunately, to perform a quantitative assessment, the time-consuming and cumbersome manual tracing of the myocardial boundaries in all the sequence frames is required. Typical CMR perfusion image sequences are characterized by several unfavorable conditions such as relatively poor image quality, low spatial resolution, rapid changes in brightness of the different image components and unpredictable cardiac translation and deformation due to both in-plane and out-of-plane respiratory motion. These factors have been hindering the implementation of automated non-rigid registration algorithms aiming at the identification of the myocardium throughout the image sequences.

The results obtained in this study have demonstrated the high accuracy of the proposed technique, as indicated by overall Hausdorff Distances (between automatically adjusted contours and manually traced ones) around 2 pixels as well as Mean Absolute Distances on average less than one pixel. These results indicate that the proposed technique is able to identify the myocardium in a fast and reliable fashion, suitable for clinical use. Importantly, the described registration scheme is completely independent from the specific type of image sequences analyzed in this study, and could thus be applied to other kinds of image sequences as a potential solution for tracking deformable objects.

References

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