Nonrigid Motion Compensation of Free Breathing Acquired Myocardial Perfusion Data

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Abstract. In this work, we present a novel method to compensate the movement in images acquired during free breathing using first-pass gadolinium enhanced, myocardial perfusion magnetic resonance imaging (MRI). First, we use independent component analysis (ICA) to identify the optimal number of independent components (ICs) that separate the breathing motion from the intensity change induced by the contrast agent. Then, synthetic images are created by recombining the ICs, but other then in previously published work (Milles et al. 2008), we omit the component related to motion, and therefore, the resulting reference image series is free of motion. Motion compensation is then achieved by using a multi-pass non-rigid image registration scheme. We tested our method on 15 distinct image series (5 patients) consisting of 58 images each and we validated our method by comparing manually tracked intensity profiles of the myocardial sections to automatically generated ones before and after registration. The average correlation to the manually obtained curves before registration 0.89 ± 0.11 was increased to 0.98 ± 0.02.

1 Introduction

First-pass gadolinium enhanced, myocardial perfusion magnetic resonance imaging (MRI) has been proved to be a reliable tool for the diagnosis of coronary artery disease that lead to reduced blood supply to the myocardium [1]. In a typical imaging protocol, images are acquired over 60 sec to cover a full perfusion cycle, (Fig. 1), a time that is generally too long for the average patients to hold their breath. Therefore, the image series will contain breathing motion that needs to be compensated for if the myocardial perfusion is to be analyzed automatically. An additional challenge is posed by the contrast agent passing through the heart that results in a strong intensity change over time. In the following we will assume that the patient is breathing freely during image acquisition, which results in a breathing motion that is almost periodic, a property that can be exploited when this motion is to be compensated for.

Various image registration methods have been proposed to automatically compensate breathing movement. Some methods rely on rigid registration only (e.g., [2, 3]). However, since the heart moves within the non-moving chest, rigid registration requires the segmentation of a region of interest around the heart, and it also does not account for the non-rigid deformations of the myocardium.

Also, most proposed methods require the registration of images at different perfusion phases, and, therefore, need to take the intensity change into account, e.g. by employing more complex registration criterions that can be directly applied to images with varying intensity distributions [3, 4]. In [5] a two step procedure was proposed that exploits the quasi-periodicy of the free breathing motion that reduces the need to register images from different breathing phases, but it does not eliminate it completely.

Chao and Ying [6] presented a motion compensation scheme that eliminated the need to register images from different perfusion phases by modeling an approximation of ground truth and then register to it. However, the method relies on an initial rigid registration that requires the extraction of a bounding box.

Milles et al. [2] overcame the need for registration of images of different perfusion phases by using ICA to create synthetic references that exhibit similar intensities like their original counterparts. In addition, they used the ICA and prior knowledge to extract a bounding box around the left heart ventricle (LV) making rigid registration possible. However, in [5] it was discussed that the method does not perform reliably for data acquired with a free breathing protocol: The synthetic references generally contained a lot of residual movement that made it impossible to achieve complete registration, and, in some cases it was impossible to identify the RV and LV cavities, and, hence, to create a proper bounding box that is required for rigid registration.

We propose to enhance the work of Milles et al. [2] by replacing the three-component ICA by running a series of ICA that will automatically select the optimal number of ICs to separate the breathing motion from the intensity change. Based on this optimal separation, we create a series of reference images by recombining the optimal ICs omitting the motion component, resulting in a series of images that is free of motion and whose images exhibit a similar intensity distribution as their original counterparts, allowing for the application of the sum of squared differences as registration criterion. Then, non-rigid reg-

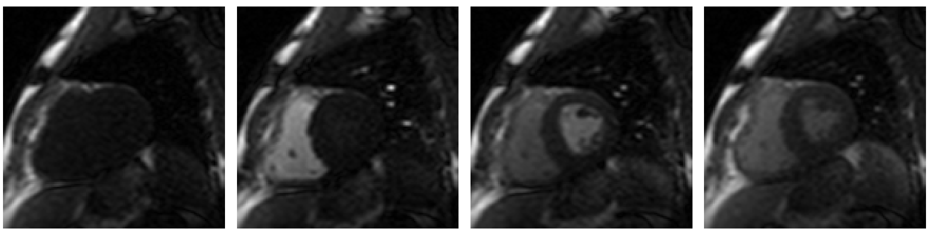

Fig. 1. Images from a first-pass gadolinium enhanced, myocardial perfusion MRI study. From left to right: pre-contrast, RV-peak, LV peak, and myocardial peak.

istration is used to compensate for the motion, eliminating the need to segment a bounding box around the heart. For full breathing motion compensation, the whole scheme is run in a multi-pass fashion.

2 Materials and Methods

Reconsidering myocardial perfusion image series acquired under a free breathing protocol, one takes note that they should actually contain five independent components (ICs): The baseline, the LV cavity enhancement, the RV cavity enhancement, the myocardial perfusion, and the quasi-periodic movement. Hence, a separation into five ICs should be optimal. However, our experiments show that depending on the image data, sometimes the perfusion component can not be separated well, and instead the movement component is split into two different ICs which results in more than one mixing curve exhibiting periodic behavior (Fig. 2, left, solid lines). Here, reducing the number of components can result in an unambiguous separation of the motion component (Fig. 2,right). In other cases, intensity change patterns resulting from the imaging process create more components that can be identified, resulting in a better separation of the movement if more than five components are used. Therefore, we run ICAs using four to six components and estimate the best separation by identifying periodic components based on curve length and mean frequency. The highest number of ICs that results in only one periodic component is then used for further processing.

To register the whole series, we create synthetic reference images for each time point by linearly combining all ICs excluding the IC corresponding to the quasi-periodic movement. By this method, the movement is removed from the image series, but the intensity change is preserved, resulting in reference images that exhibit the same intensity distributions as their original counterparts.

Hence, our registration approach uses the sum of squared differences as registration criterion. It utilizes a B-Spline model for the transformation [7] and a regularization that is based on the separate norms of the second derivative of each of the deformation components [8] weighted by a factor κ. In the first

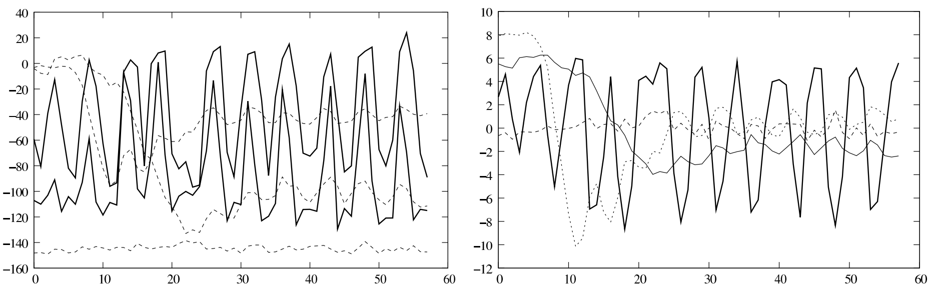

Fig. 2. Left: Mixing matrix obtained using a five component ICA. Note, that the quasi-periodic movement component is actually split into two components. Using a four component ICA results in better separation (right).

pass, we restrict the freedom of the non-rigid registration by employing a high regularization weight ($\kappa = 20$), and by using a large knot spacing (32 pixel) for the B-spline based transformation. In each subsequent pass, we then reduced the regularization weights and the B-spline knot spacing by factor of $\frac{1}{4}$. Initially, the synthetic references are quite blurry, therefore, we used a multi-pass scheme like proposed in [2]. Processing stopped after a maximum of three passes, or if in the the last processing pass no periodic motion component could be identified.

For five subjects first-pass contrast-enhanced myocardial perfusion imaging data sets were acquired and processed under clinical research protocols. All data was acquired using a free breathing protocol and motion correction was performed for three short-axis slices of these five patients covering different levels of the LV myocardium (basal, mid, and apical levels).

A gold standard for validation was acquired by manually segmenting the myocardium into 12 distinct sections and tracking their average intensity over time. Validation was then executed by comparing the manually obtained time-intensity curves to automatically obtained ones before and after registration. As a measure of similarity between these curves we used Pearsons correlation coefficient R^2 between the manual and the automatically obtained curves.

3 Results

We were able to achieve full motion compensation for all 15 image series. The average correlation between the manual and automatically obtained time-intensity curves before registration 0.89 ± 0.11 was increased to 0.98 ± 0.02 (Fig. 3), an improvement over the value of 0.96 ± 0.05 that was achieved by employing the method published in [5].

4 Discussion and Conclusions

The use of ICA as proposed in [2] provides an easy way to create synthetic reference images with intensity distributions that are close to counterparts from the

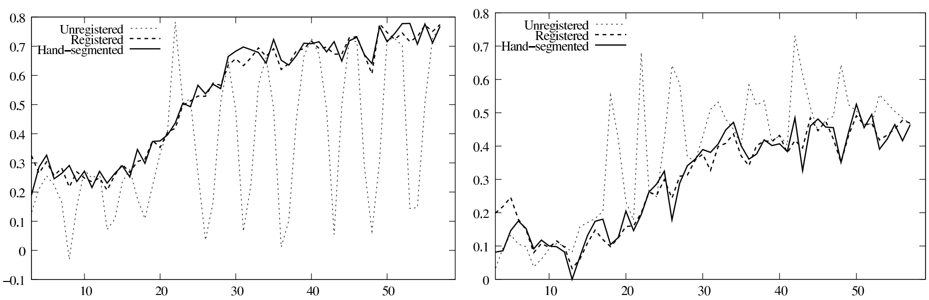

Fig. 3. Time intensity curves of two different sections of the myocardium in one image series. Note the quasi-periodic intensity change in the unregistered series and the good approximation of the manually segmented curves by the registered series.

original series making image registration easier. However, the three component approach and the use of rigid registration is not well suited for perfusion image series acquired with a free breathing protocol.

Therefore, we presented a change to this ICA based motion compensation approach that estimates automatically the optimal number of retained ICs to be used. By identifying the movement component and then eliminating it from the reference image creation, we were able to create series of reference images that exhibit no movement at all and also exhibit similar intensity distributions like the original images. By using nonrigid registration, the need for the segmentation of a bounding box around the LV myocardium was eliminated. Because of the initial blurriness of the synthetic reference images, a multi-pass scheme was employed that would put a high penalty on the nonrigid transformations in the first registration pass, and give more freedom to the transformation in subsequent passes, when the newly created reference images are less blurry.

In the approach we presented, a free breathing image acquisition protocol is a requirement, because otherwise it is difficult to identify and hence, eliminate the movement component by using ICA. However, a free breathing protocol for image acquisition also makes the procedure easier for the patient.

Currently, our approach uses a registration scheme that is run on a slice-by-slice bases. Future work will target to achieve a one-step registration of the whole sequence by modeling the time-dependency of the quasi-periodic motion.

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