3D Non-rigid Motion Correction of Free-Breathing Abdominal DCE-MRI Data

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Abstract. Inflammatory bowel diseases (IBD) constitute one of the largest healthcare problems in the Western World. Grading of the disease severity is important to determine treatment strategy and to quantify the response to treatment. The Time Injection Curves (TICs) after injecting a contrast agent contain important information on the degree of inflammation of the bowel wall. However, respiratory and peristaltic motions complicate an easy analysis of such curves since spatial correspondence over time is lost. We propose a gated, 3D non-rigid motion correction method that robustly extracts time intensity curves from bowel segments in free-breathing abdominal DCE-MRI data. It is shown that the mean TICs in small bowel segments could be robustly computed and contained less fluctuations than prior to the registration.

Keywords: Inflammatory bowel disease, small bowel, DCE-MRI, motion correction, time intensity curves.

1 Introduction

Inflammatory bowel diseases (IBD) constitute one of the largest healthcare problems in the Western World. It affects over 1 million European citizens alone, 700,000 of who suffer from Crohn's disease. Grading of Crohn's disease severity is important to determine treatment strategy and to quantify the response to treatment.

Colonoscopy in combination with the assessment of biopsy samples is considered the reference standard for diagnosis and assessment of all IBD. However, the procedure is invasive and requires extensive bowel preparation, which is considered very burdensome by most patients. Moreover, it only gives information on superficial abnormalities.

The project called VIGOR++, in which the research presented in this paper is performed, aims to create a noninvasive procedure for improving grading of Crohn's disease severity by means of magnetic resonance imaging (MRI).

Specifically, in Dynamic Contrast Enhanced MRI (DCE-MRI), the Time Injection Curves (TICs) after injecting a contrast agent are expected to contain important information on the degree of inflammation of the bowel wall. The advent of high temporal resolution scanning protocols has opened the way to TIC-measurements over

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longer time intervals during free breathing. However, respiratory and peristaltic motions complicate an easy analysis of such curves since spatial correspondence over time is lost.

Therefore, the data analysis should comprise a 3D motion correction procedure. Previous work included motion tracking in rats [1] and 2D non-rigid registration of cardiac data [2].

We propose a 3D non-rigid motion correction method that robustly extracts time intensity curves from bowel segments in free-breathing abdominal DCE-MRI data.

2 Methods

2.1 Data Acquisition

DCE-MRI data were acquired during free-breathing of 7 consenting subjects on a 3.0T Philips Intera scanner using a 3D spoiled gradient echo sequence. The scan parameters were: scan matrix 200x200, in plane resolution 2x2 mm, 14 coronal slices, slice thickness 2.5 mm, TE/TR =1.0/2.2 ms, flip angle 6°, temporal resolution 0.8 s, total scanning time 6.1 minutes. Buscopan was administered to the subjects to minimize bowel movement. A contrast agent (Gadovist) was injected (0.1 ml/kg) after the 10th image volume was acquired. As such 450 3D image volumes were acquired capturing the inflow and outflow of the contrast medium. Fig.1 demonstrates the high spatial and temporal resolution of our data (notice the small bowel segments and the effects of the respiratory cycle).

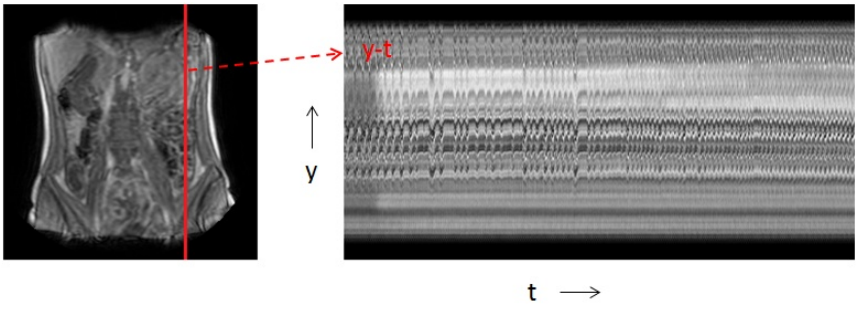

Fig. 1. Illustration of the high spatial and temporal resolution of data. The left image is one randomly selected coronal slice. The right image shows the intensity along the red line(vertically) over time (horizontally).

2.2 Respiratory Gating

The focus of our interest is the varying contrast uptake that is reflected in the MRI signal value. During contrast uptake there is respiratory and bowel movement. Unfortunately, a simple motion correction by means of registration cannot be applied. This

is because susceptibility effects influence the MRI signal values. These susceptibility effects make that the image intensity varies as a function of position in the scanner. What is more, the respiration imposes a discontinuous deformation to the bowel structures which is usually not incorporated in a non-rigid deformation models.

We hypothesize that retrospective gating to one phase of the respiratory cycle reduces the abovementioned effects to a large extent. Accordingly, we computed in each patient the Sum of Squared Differences (SSD) of all dynamically acquired 3D volumes to a selected dynamic (here we simply chose middle dynamic, i.e. number 225):

$$D_n = \sum_i (f_n(\boldsymbol{X}_i) - f_{middle}(\boldsymbol{X}_i))^2 \quad (1)$$

in which $f_n(\boldsymbol{X}_i)$ is the intensity of each voxel of dynamic n and D_n is the SSD of volume n to the middle dynamic. The oscillatory behavior of D_n (reflecting the breathing cycle) is shown in Fig.2.

Subsequently, we selected those 3D images that corresponded to the local minima of the oscillatory curve based on the Gaussian-weighted second-order derivative. This delivers a gated subset of the original data, representing volumes in the same phase of respiratory cycle. However, the images are not well registered, particularly due to bowel motion.

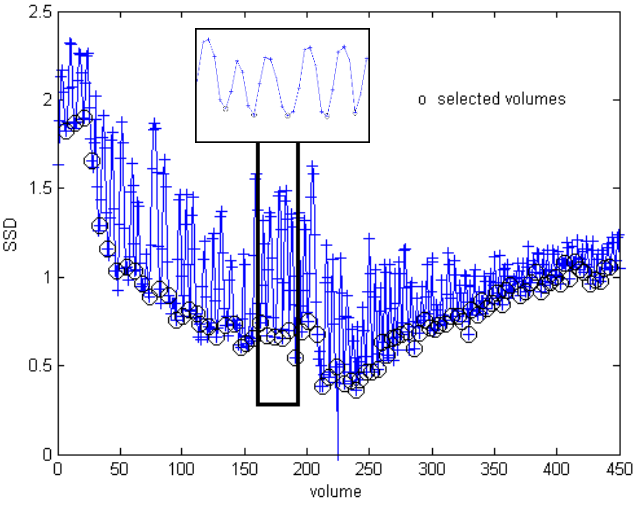

Fig. 2. Illustration of the oscillatory of D_n. The black rounds correspond to the selected subset of images that are in the same breathing phase.

2.3 Image Registration

A non-rigid registration procedure was adopted to compensate for the remaining misalignment. Thereby, we first selected a reference dynamic from the subset of images that

are in the same respiratory phase. We chose as a reference the one dynamic with the lowest accumulated SSD with respect to the other dynamics within the subset:

$$D_s = \sum_i \sum_j (f_s(\boldsymbol{X}_i) - f_j(\boldsymbol{X}_i))^2 \tag{2}$$

$$f_{ref} = f_{\min D_s} \tag{3}$$

Here D_s is the accumulated SSD for dynamic s to the other volumes in the subset.

Now, the next step is to non-rigidly register the subset of images to the reference image from (3). To do so, we adopted a Discrete Cosine Transformation (DCT) model [3] with two successive cut-off values applied to the DCT basis functions of 50 and 25 mm. The first cut-off value serves to achieve global registration and particularly corrects for any remaining displacement due to breathing (predominantly taking place in the x-y plane). The second, smaller cut-off was chosen to correct for smaller movement like peristalsis.

The DCT model we used here is a nonlinear spatial transformation. The transformation is defined in 3D as follows:

$$x_i' = x_i + \sum_{j=1}^{J} p_{xj}\, b_{1j}(\boldsymbol{X}) \quad y_i' = y_i + \sum_{j=1}^{J} p_{yj}\, b_{2j}(\boldsymbol{X}) \quad z_i' = z_i + \sum_{j=1}^{J} p_{zj}\, b_{3j}(\boldsymbol{X})$$

where x_i, y_i, z_i are the coordinates of a voxel $\boldsymbol{X}$ in the image that needs to be transformed and x'_i, y'_i, z'_i are the new coordinates after transformation. Furthermore, p_{xj}, p_{yj}, p_{zj}, are the jth coefficient of the cosine functions for each spatial dimension and J is number of basic functions. $b_{1j}(\boldsymbol{X})$, $b_{2j}(\boldsymbol{X})$, $b_{3j}(\boldsymbol{X})$ represent the jth cosine function at position $\boldsymbol{X}$ defined as follows:

$$b_{mj}(\boldsymbol{X}) = \sqrt{\frac{1}{J}} \qquad j = 1, m = 1 \ldots M \tag{4}$$

$$b_{mj}(\boldsymbol{X}) = \sqrt{\frac{2}{J}} \cos\left(\frac{\pi(2m-1)(j-1)}{2J}\right) \qquad j = 2 \ldots J, m = 1 \ldots M \tag{5}$$

In fact, the transformation is based on a linear combination of low spatial frequency cosine basis functions to reduce the number of coefficients.

2.4 ROI Annotation and Segmentation

The effectiveness of the registration procedure was evaluated by assessment of the TIC curves in three ROIs (region of interests). These three ROIs were manually annotated in 3D by an expert in small parts of the bowel wall in various locations in the abdomen, using ITK-SNAP software (itksnap.org). The ROIs were drawn in the reference image delivered by Equation 3 (see also Fig.4, inset, dark blue color). A simple segmentation procedure based on isodata thresholding [4] was applied to discard the voxels relating to the bowel lumen from each ROI and retain the bowel wall voxels (which is the focus of our interest, Fig.4, inset, bright blue color).

3 Experimental Results

Notice that each patient initially delivers 450 dynamically acquired 3D images consisting of 224x224x14 voxels(The images were interpolated in the in- plane area. The inplane resolution was changed from 2.0*2.0mm to 1.8*1.8mm). The gated subset (see Section 2.2) contained 80-120 volumes (range over the 7 included patients). Fig. 3 shows the initial time-averaged image as well as this same image after registration procedure. It demonstrates the increase in anatomical detail, for example at the bowel walls. The average TICs in the ROIs in the original and processed dataset are compared in Fig. 4 (notice the reduced number of volumes in the gated dataset). ROI #3 (red) is of relatively large size and contains negligible motion due to its location in the lower abdomen. ROIs #2 (green) and #1 (blue) have smaller sizes and are positioned more proximate to the lungs. Clearly, a dramatic increase in contrast in the processed dataset is visible in the latter areas.

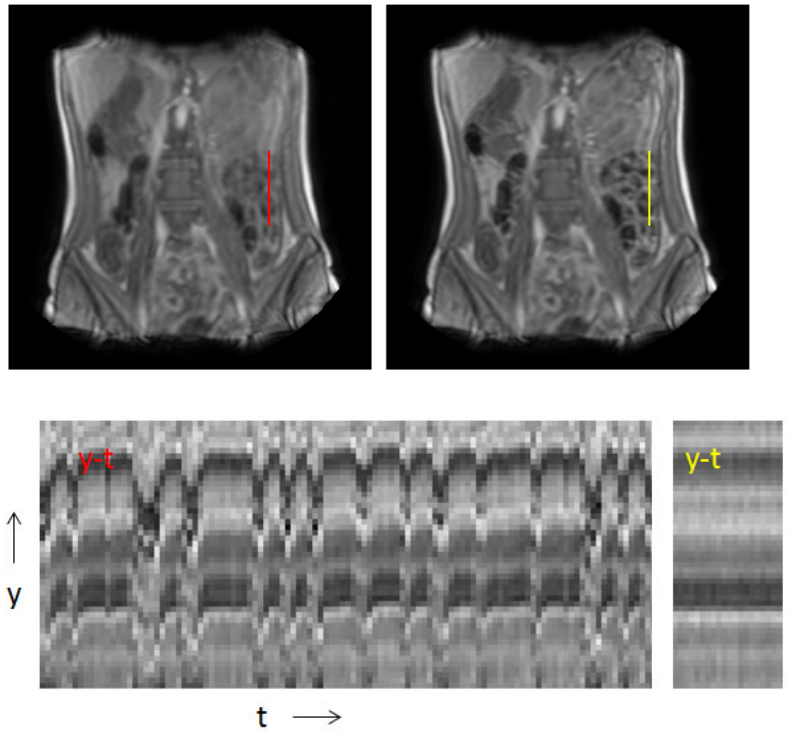

Fig. 3. Top: comparison of time-averaged images before (left) and after registration (right). These mean images are calculated over the 7 included patients. Bottom: intensity (vertically) over time for the profiles indicated in the top images from one patient, i.e. before (left) and after registration (right). Notice that the bottom right image is taken from the gated subset, which is why the bottom two images have different scale.

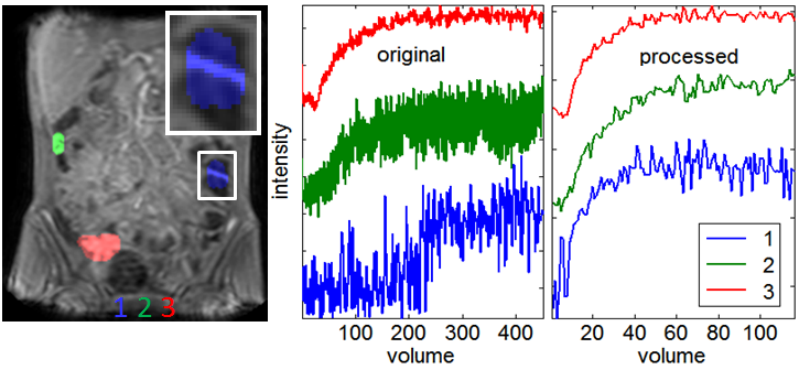

Fig. 4. Left: Three ROIs are annotated in 3D and processed to segment the bowel wall, c.q. remove lumen and air (dark/bright blue, inset). Right: Mean Time Intensity Curves (TICs) over the ROIs in the original and processed datasets are plotted.

4 Discussion

We have presented a method to correct for motion in free-breathing DCE-MRI data. The mean TICs in small bowel segments could be robustly computed and contained less fluctuations than prior to the registration. We aim to proceed now to a voxel-based TIC reconstruction. For that, contrast change modeling [2] and time-constrained registration may be beneficial. Also, we have found that the linear model underlying the DCT transform is not flexible enough for some situations. Fig.5 shows misalignment around the bowel wall after registration. It demonstrates that the bowel wall is hardly warped in the annotated rectangles. In fact, a more flexible transforms such as B-spline transform may yield a better registration result. Moreover, the SSD similarity does not account for the contrast variation that is inherently present in images. Therefore mutual information might be a better metric [5].

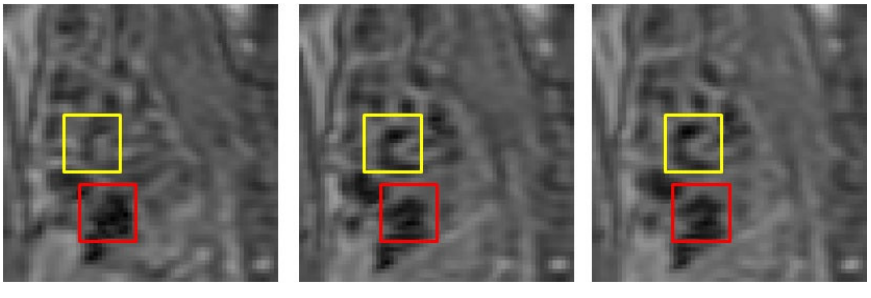

Fig. 5. Left: reference volume (t=225). Middle: volume (t=128) before registration. Right: volume after registration.

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