Motion Correction of Cardiac PET Using Mass-Preserving Registration

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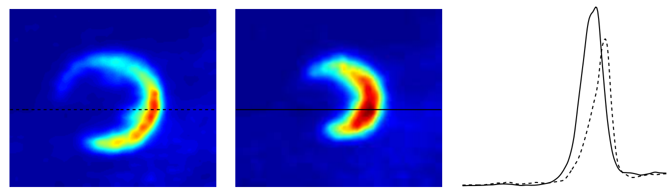
***Abstract*—Cardiac motion leads to image quality degradation in positron emission tomography (PET). In the literature gated listmode acquisition along with motion estimation techniques, such as optical flow or image registration, proved successful for respiratory motion correction. Cardiac gated PET images, however, are affected by the partial volume effect (PVE) which is expressed in strongly varying local intensities. This fact complicates the motion estimation process. To overcome this problem, the mass-preserving nature of PET images is identified and included into the image registration problem. We show that our mass-preserving registration approach allows cardiac motion correction with high accuracy due to realistic motion estimates. In addition, neglecting the mass-preserving property of PET is proven to entail unrealistic results.**

***Index Terms*—Motion Correction, PET, Gating, Image Registration, Mass-Preservation.**



(a) Diastole (b) Systole (c) Line profiles

Fig. 1. The diastole and systole for one patient is shown in Figures 1(a) and (b). In Figure 1(c) two line profiles from these 2D slices (out of a 3D dataset) are shown. It can be observed that the maximum peaks in these line profiles vary a lot due to the PVE.

I. Introduction

CARDIAC and respiratory motion cause severe artifacts and spatial blurring in PET images due to relatively long acquisition times [4]. One way to overcome the problem of motion is to use gating for separating the PET dataset into cardiac (and/or respiratory) phases. A benefit of gating is the reduction of motion in each gate, but at the cost of a higher noise level. In order to compensate for this loss of image quality, all gates can be brought into a common frame via registration and combined afterwards in an averaging step.

Different motion correction schemes have been proposed for respiratory PET data, such as optical flow based approaches [3] or spatio-temporal registration methods using B-splines [1]. While respiratory motion is more or less locally rigid, cardiac motion is highly non-linear. Therefore intensities at corresponding points in cardiac gated PET can vary a lot between systole and diastole due to the partial volume effect (PVE) (see Figure 1). These local intensity variations are challenging for registration methods trying to match points with similar intensities. Thus, most motion correction techniques in the literature, like the above mentioned methods, are not directly suitable for motion correction in cardiac gated PET.

In this paper we propose to enter prior knowledge about the nature of PET data into the transformation model for image registration to overcome the problem of intensity changes. This prior knowledge is the preservation of mass (respectively radioactivity) over the whole image. We introduce this mass-preservation property in combination with a variational registration approach. This leads to a non-parametric transformation model, well suited for (large) nonlinear deformations and independent of costly evaluation of basis functions. The effectiveness of mass-preserving registration is demonstrated in a cardiac gated PET study of 15 patients.

II. Methods

We propose a mass-preserving image registration method to overcome the problem of strongly varying local intensities in cardiac gated PET. The procedure is threefold: 1. Cardiac gating, 2. Mass-preserving motion correction of the gates, 3. Averaging in one common frame. The first step is performed with a listmode-driven gating technique [2]. Averaging of the motion corrected gates in the last step intends to utilize the full statistics for quality improvement (not shown in this work). We will concentrate on the second step in the following.

A. Mass-preserving image registration

As a property of gating, all gates are formed over the same acquisition time interval. Hence, the total amount of radioactivity in each phase is approximately equal. We call this property *mass-preservation* (MP). The aim is to include this prior knowledge into a variational registration formulation.

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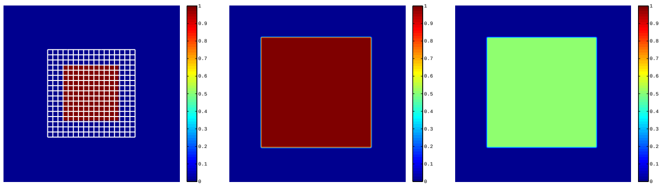


(a) Square + Grid (b) After transformation w/o accounting for MP (c) After transformation w/ accounting for MP

Fig. 2. Principle of a mass-preserving transformation: The square in Figure 2(a) is transformed according to the superimposed grid. The transformation grid describes a scaling with factor two. Simply applying the transformation results in the transformed square in Figure 2(b). Accounting for mass-preservation means that the total amount of mass must not change due to applying a transformation. Thus, the intensities have to be modulated according to the volumetric change as shown in Figure 2(c). The intensity modulation factor is expressed by the Jacobian determinant as we will see in Equation (1).

Each template gate $\mathcal{T}$ is registered onto one assigned reference gate $\mathcal{R}$. This yields a transformation y representing point-to-point correspondences between gate $\mathcal{T}$ and $\mathcal{R}$. In order to find an optimal y, the following functional has to be minimized:

$$\min_{y} \; \mathcal{D}\left[(\mathcal{T} \circ y) \det(\nabla y), \; \mathcal{R}\right] + \alpha \, \mathcal{S}\left[y\right] \; . \tag{1}$$

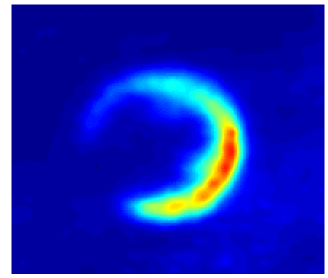
Here $\mathcal{D}$ denotes the sum-of-squared differences (SSD) distance functional and $\mathcal{S}$ an elastic regularization functional. The positive real number α balances between minimizing the SSD and retaining smooth transformations.

Compared to standard image registration the characteristic feature in Equation (1) is the incorporation of a mass-preserving transformation model. In addition to only deforming the template volume during registration. This is done by multiplying with the transformation's Jacobian determinant $\det(\nabla y)$. The Jacobian determinant expresses the volumetric change due to the transformation y as expressed in the theorem of integration by substitution of multiple variables. For instance, when doubling the volume of one voxel, the radioactivity contained in this voxel distributes over a volume twice as large and is thus halved. Hence, the mass - or radioactivity in our case - is preserved. This principle is illustrated with a simple example in Figure 2.

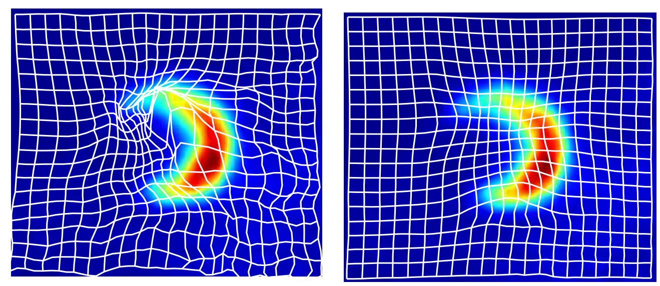
III. Results

We implemented 3D mass-preserving registration based on the freely available FAIR toolbox [5] in MATLAB®. FDG-PET data of 15 cardiac patients were processed by gating (10 cardiac gates) and motion corrected by applying our algorithm. The gate showing the diastole was chosen as the reference image whereas the remaining nine gates served as template images.

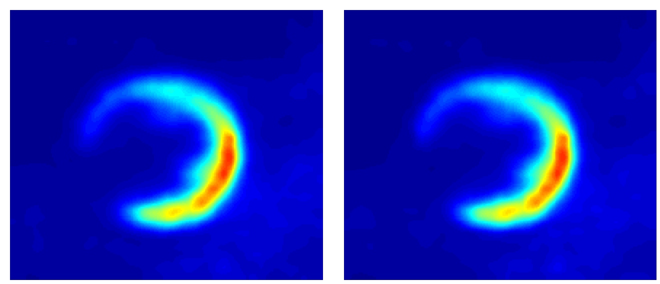
The necessity of accounting for mass-preservation in cardiac gated PET is illustrated in Figure 3 for one patient. The template image $\mathcal{T}$ (systole) was registered to the reference image $\mathcal{R}$ (diastole) once with and once without accounting for mass-preservation. The local intensity differences between the two cardiac phases can be clearly observed. Although the resulting template image without mass-preservation looks



(a) Reference $\mathcal{R}$ (diastole)



(b) $\mathcal{T}$ (systole) + Grid without MP (c) $\mathcal{T}$ (systole) + Grid with MP



(d) Result without MP (e) Result with MP

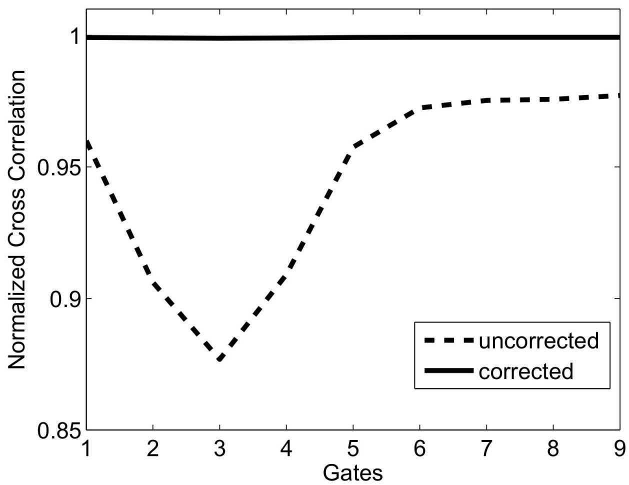
Fig. 3. Comparison of motion correction with and without accounting for mass-preservation of cardiac gated PET (short axis view of the left ventricular myocardium). The template image $\mathcal{T}$ was registered to the reference image $\mathcal{R}$.

convincing at first glance, the transformation grid in Figure 3(b) reveals the side effects of neglecting mass-preservation. Foldings and unrealistic irregularities in the grid suggest the need for fundamental improvement of the registration task.

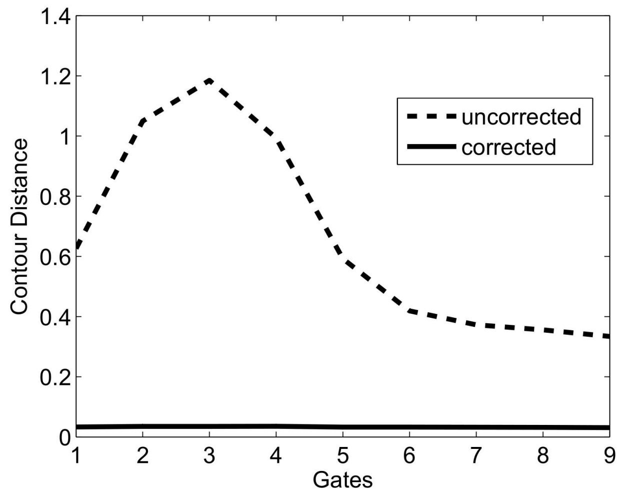
In contrast, mass-preserving registration features a smooth and realistic transformation, shown in Figure 3(c). The relaxation of the heart is clearly visible in the grid. Further, the resulting image perfectly matches the reference image.

A. *Patient study*

On average over all 15 patients the normalized cross-correlation (NCC) increased from 0.8789 ± 0.0462 to 0.9989 ± 0.0003 for the systole (third) gate. The systole gate is the most challenging case due to the strongest heart motion compared to the reference gate (diastole). The average NCC before and after mass-preserving registration for each gate is plotted in Figure 4(a). We additionally analyzed the pixelwise distance of threshold segmented heart contours. The threshold was chosen manually. For the systole gate the mean contour distance decreased from 1.2146 ± 0.4495 voxels to 0.0368 ± 0.0116 voxels. The mean contour distances for all gates before and



(a) Normalized cross-correlation



(b) Mean contour distance

Fig. 4. Average registration results for 15 cardiac gated PET datasets. Each dataset consists of 10 cardiac gates. For each gate (except for the reference gate) the NCC and the mean contour distance to the reference gate is plotted.

after mass-preserving registration are shown in Figure 4(b).

IV. Discussion

Motion correction of cardiac gated PET was successfully performed in a human patient study. Image degradation due to motion was reduced significantly and smooth and physically meaningful motion estimates were achieved. The necessity of accounting for mass-preservation during registration of PET images was demonstrated. In contrast to other motion correction techniques [1], [3] our mass-preserving transformation model is able to correct cardiac gated PET with its PVE induced local intensity changes.

One goal for future research is the application to dual gated PET. Instead of averaging, a motion corrected reconstruction might further improve image quality.

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