Respiratory motion correction with an improved demons algorithm for PET images*

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Abstract: Respiratory motion is a major factor that affects the quality of PET images of the thoracic area. The diaphragm moves about 15–20 mm due to respiratory motion, which substantially degrades the effective spatial resolution of PET. In this paper, a gated acquisition method is used to correct the motion effects. In this method, an improved demons algorithm is proposed to align the gated images. The experimental results show that the quality of PET images is significantly improved when using our improved method and the proposed method has a faster convergence rate than the original demons algorithm.

Key words: motion correction, demons algorithm, discontinuity, PET

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1 Introduction

Positron emission tomography (PET) is a molecular imaging technique which provides functional information about the human body. However, respiratory motion is a major challenge to the quality and accuracy of PET images. A typical PET scan takes about 15–30 minutes, therefore respiratory motion is inevitable during this period. The diaphragm moves about 15–20 mm due to respiratory motion [1]. This distance is far beyond the current PET scanners' spatial resolution of approximately 3–5 mm. So, respiratory motion substantially degrades the effective spatial resolution of PET. In addition, the respiratory motion can lead to incorrect judgements about lesions in the lungs. So it is very important to overcome the motion effects in PET.

A common method used to overcome the motion effects in PET is gated acquisition [2]. This method divides a respiratory cycle into a number of time slots which are called gates and the coincidence events in each slot are collected separately [3]. Because the time is very short in each gate, a motion-free image can be reconstructed for each gate. The traditional method just takes single-gate reconstruction, while it only uses a part of the coincidence events which result in noisy images. In order to maintain image quality, it must prolong the scan time or increase the radiotracer dose. Neither of these methods is good. At present, a number of methods to estimate the motion between the gated images have been proposed. These methods can make use of all the coincidence events and overcome the difficulties faced when using the traditional method. They include the aligning of the reconstructed gated images into the same position and the summation of the images [4–7], the incorporation of the estimated motion in the reconstruction process [8, 9], and the rebinning of the list-mode data according to the estimated motion prior to reconstruction [10]. In practice, the last two methods have many problems. Firstly, the method of incorporating estimated motion in the reconstruction process needs to estimate the motion with other imaging devices such as computed tomography (CT). Lamare et al. used the registration of the gated CT images to obtain accurate motion estimates, which significantly increases

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the radiation burden to the patient. Secondly, the method of rebinning the list-mode data is just applicable to rigid motion. The method of summation of aligned images is the most popular and the easiest method. Dawood et al. have proposed to align the gated PET images by using the Lucas-Kanade algorithm and sum the aligned images [4]. Bai et al. have also proposed to register the gated PET images by using the regularized B-spline deformable registration method and sum the aligned images [6]. While the Lucas-Kanade method is unsuitable for solving large-scale transformation, the B-spline deformable registration method does not correct the local small deformation well. In this paper, we proposed a novel method which also belongs to the method of summation of aligned images to correct for motion effects in PET data. This method well solves the problems mentioned previously. It uses an improved demons algorithm to align the gated PET images. The demons algorithm has also been used to solve the motion effects in CT data [11]. However, in the demons algorithm proposed by Thirion [12], and improved by Wang [13], when they use a Gaussian smooth filter to smooth the deformation field, they do not consider the discontinuities across the boundaries of moving objects. So it has a negative impact of smoothing out the deformation field across the boundaries and then results in a low convergence rate. In our study, a novel method which reduces the smooth effect in areas of discontinuity and retains the effect in areas of homogeneous deformation field such as inside the objects is proposed. The convergence rate of the demons algorithm is obviously improved with our proposed method. The experimental results show that the quality of PET images is significantly improved with our improved method.

This paper is organized as follows. The proposed method is presented in Section 2. The test data are described in Section 3. The experimental results are as shown in Section 4. Finally, a conclusion and a discussion are given in Section 5.

2 Methods

2.1 Respiratory gating

The coincidence events obtained by a PET scan are divided into eight parts according to a respiratory signal which is acquired from the patient by a video camera or by a chest belt. Each part corresponds to a particular phase of the respiratory cycle. The PET image reconstructed with each part data contains only slight motion and can be regarded as static. At present, time-based and amplitude-based gating strategies can be used. The time-based gating which also can be called phase gating, sorts the data

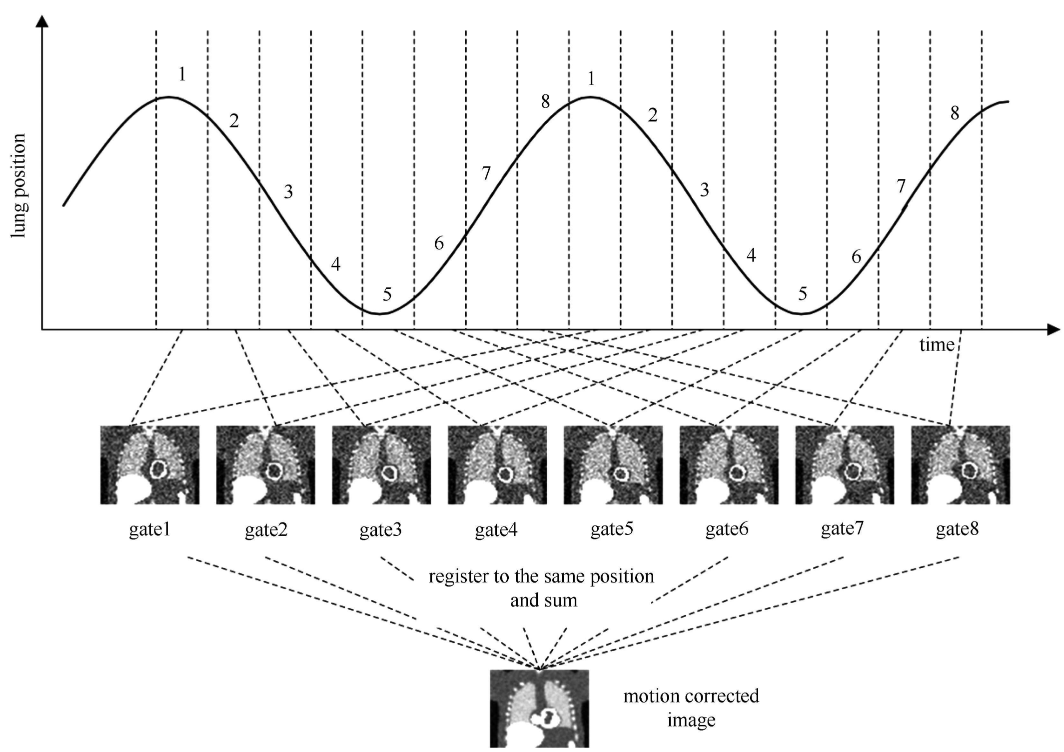

Fig. 1. Illustration of the gating and motion correction scheme.

according to time in each respiratory cycle. The amplitude-based gating sorts the data according to the amplitude of the respiratory signal. The amplitude-based gating is better than time-based gating because it can solve an irregular breathing pattern. However, the amplitude-based gating is complicated and difficult to realize in practical application. In this paper, the time-based gating method is used for experiments, but the proposed method can also be used to process the amplitude-based gated data. When the eight gated images are obtained, they are registered to the same position with our proposed improved demons algorithm and then summed. The final corrected image will be obtained in this way. Fig. 1 illustrates our gated method.

2.2 Improved demons algorithm

The optical flow equation is used as the basis of the demon registration forces in the demons algorithm proposed by Thirion [12]. For a given point p in a static image F, the estimated displacement $\vec{u}$ for it to match the corresponding point in the moving image M is given by the following equation:

$$\vec{u}=\frac{(m-f)\vec{\nabla}f}{\left|\vec{\nabla}f\right|^2+(m-f)^2}, \tag{1}$$

where $\vec{u}=(u_x,u_y,u_z)$, f is the intensity in the static image and m is the intensity in the moving image. $\vec{\nabla}f$ is the gradient of the static image. The $\vec{\nabla}f$ represents an internal edge based force. The $(m-f)$ term is the external force. Since the displacement $\vec{u}$ is based on local information, Gaussian smoothing of the velocity field is included as regularization. The demon equation is a local approximation, thus it needs to be solved iteratively to register two images. The following steps detail the demons algorithm:

-Choose a starting spatial transformation (a vector field) $\vec{s}$.

-Iterate the follow steps until convergence.

1) Given $\vec{s}$, compute a correspondence update field $\vec{u}$ by minimizing E:

$$E(\vec{u})=\|F-M\circ(\vec{s}+\vec{u})\|^2+\frac{\sigma_i^2}{\sigma_x^2}\|\vec{u}\|^2. \tag{2}$$

2) If a fluid-like regularization is used, let $\vec{u}\leftarrow K_{\text{fluid}}\times\vec{u}$. The convolution kernel K_{fluid} is typically a Gaussian kernel.

3) Update the transformation field $\vec{s}\leftarrow\vec{s}+\vec{u}$

where F is the static image, and M is the moving image. $\circ$ represents the image transform. σ_i and σ_x are the constants for intensity uncertainty (image noise) and transform uncertainty, respectively.

The method described above is the original demons algorithm, which only uses the edges in the static image as passive internal force. He Wang et al. proposed adding an equation with the image edge forces of the moving image that improves the registration convergence speed and stability [13]. The following is the equation.

$$\vec{u}=\frac{(m-f)\vec{\nabla}f}{\left|\vec{\nabla}f\right|^2+\alpha^2(m-f)^2}+\frac{(m-f)\vec{\nabla}m}{\left|\vec{\nabla}m\right|^2+\alpha^2(m-f)^2}, \tag{3}$$

where α is a normalize factor that allows the force strength to be adjusted adaptively. An α value that is too large will get too small deformations, and a too small α value will get too large deformations, while the right deformations will make the registration algorithm more accurate and fast. So to get an appropriate value for α, different values for α were tested in our method. Fig. 2 illustrates the experimental results. From the results, it can be found that the sum of squared difference (SSD) of two images is the smallest after registration when the α value is about 2.5. So the value of α is 2.5 in our method.

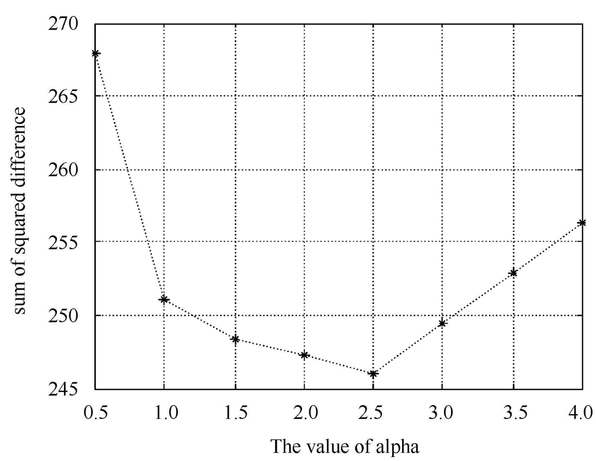

Fig. 2. The SSD values of two images after registration by our proposed demons algorithm with different alpha values.

In this work, the demons algorithm proposed by Wang et al. is improved. The second step, Gaussian smoothing, is the focus of our improvement. In the demons algorithm, when it uses a Gaussian smooth filter to smooth the deformation field, it does not consider the discontinuities across the boundaries of moving objects. So it has a negative impact of smoothing out the deformation field across the boundaries and then results in a low convergence rate. We propose a method to reduce the smooth effect in areas of discontinuity and retain the effect in areas with a homogeneous deformation field such as inside the objects. This method uses the image gradient to weight the deformation field and then smoothes the weighted deformation field with Gaussian filters. Thus, places where edges are present will be smoothed less than areas inside organs which usually have fewer edges and a lower gradient. The weighted method is given by

$$\vec{u} \leftarrow K_{\text{fluid}} \times \left(\left(1 + \left\| \vec{\nabla} m \right\| \right) \vec{u} \right). \tag{4}$$

3 Test data

The four-dimensional nonuniform rational B-splines (NURBS)-based cardiac-torso (NCAT) phantom was developed to provide a realistic and flexible model of the human anatomy and physiology for use in nuclear medicine imaging research [14]. The organ models are based on NURBS. It contains all organs inside the torso and simulates PET emission and CT scans. It models common patient motions such as the cardiac and respiratory motions. A coronal view of the phantom is given in Fig. 3(a).

Fig. 3. (a) Coronal view of the NSCT phantom simulating PET data without noise; (b) the part we used.

The phantom software also provides the option of saving the data in different respiratory or cardiac gates. This option is used to obtain eight respiratory gated data. The phantom software allows setting the degree and period of motion of different organs manually. According to the studies [1], the respiratory period was set to 5s, and the maximum magnitude of the diaphragm motion was set to 20 mm in our experiments. In order to speed up the computation, we just utilized the torso data containing the heart, lung, and liver. Fig. 3(b) is the coronal view of the data we used. The original data are noise free and so Gaussian white noise with mean 0, and 0.0001 variance is added to the phantom data to make them more analogous to the real data.

4 Results

4.1 Evaluate criteria

To evaluate the registration effect by our proposed method, an appropriate criterion must be selected. Many such evaluation methods have been proposed in Ref. [15]. The correlation coefficient (CC) is chosen as the evaluation criterion in our paper. Because the images we used are the same modality, the CC is the most appropriate criterion. On the other hand, it is has also been used to evaluate the motion correction problem by other authors. The CC is defined as:

$$CC = \frac{\sum (x-X)(y-Y)}{\sqrt{\sum (x-X)^2 \sum (y-Y)^2}}, \tag{5}$$

where x, y are the values from two data sets and X, Y are the mean values of the two data sets.

4.2 Motion correction

The forth gated image is taken as the target gate in the breathing cycle. All other gated images are registered to the target gated image by our proposed improved demons algorithm. Lastly, the aligned gated images are summed to an image and then the corrected PET image is obtained. Fig. 4 shows the corrected results. It can be found that the improvement due to motion correction is evident. In particular, the motion of the heart due to respiration was corrected to a large extent. (c) and (d) in Fig. 4 are the corrected images with the original demons algorithm and our proposed improved demons algorithm, respectively. The same iteration number is used in the original demons algorithm and our proposed method. It is difficult to observe the improvement of our proposed method from the results. However, the difference can be found from the quantitative analysis.

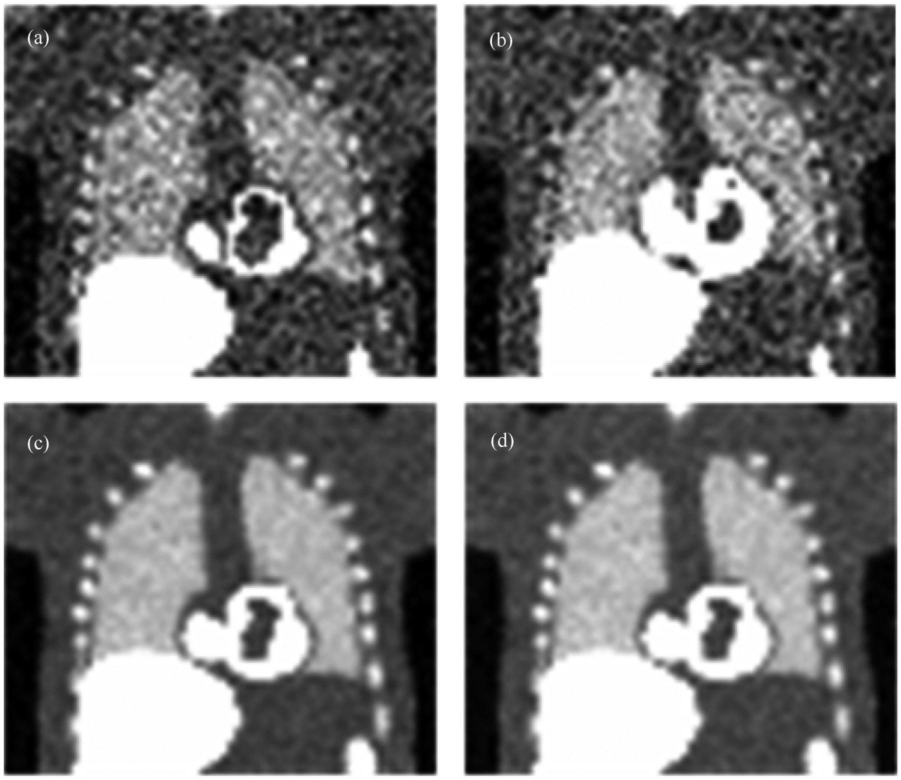

Fig. 4. Result with the noisy phantom data (coronal slice). (a) is the forth gated data, the target gate; (b) is the sum of eight uncorrected datasets; (c) is the sum of eight corrected datasets with the demons algorithm; (d) is the sum of eight corrected datasets with our proposed method.

Table 1. The improvement of the motion correction (CC).

	gate4	gate1	gate2	gate3	gate5	gate6	gate7	gate8
original	1.0000	0.7325	0.7989	0.9264	0.9732	0.9325	0.8307	0.7670
demons algorithm	1.0000	0.9809	0.9825	0.9877	0.9874	0.9889	0.9874	0.9798
our proposed	1.0000	0.9834	0.9848	0.9887	0.9878	0.9894	0.9886	0.9820

The CC is used to evaluate the improvement of the motion correction and the distinction between our proposed method and the original demons algorithm. Table 1 gives the CCs between gates 1 to 8 and the target gate before and after motion correction. The first line in the table is the CCs between gates 1 to 8 and the target gate before correction. The next two lines are the CCs after correction by using the demons algorithm and our proposed method. It is obvious that the CCs are almost close to 1 after motion correction, which means the gated images are well aligned with the forth gated image. So the final corrected image obtained by summing the eight aligned images will be good. The CCs between the target gated image and the aligned gated images by the proposed method are closer to1 than by the original demons algorithm, which means the registration results are better with our proposed method. So the final corrected image obtained by using our proposed method will also be better.

4.3 The improvement of the proposed method

To prove that the proposed method is superior to the original demons algorithm, the first gated image and the second gated image are registered with the proposed method and the original demons algorithm respectively. The SSD of the two images is compared after registration. Fig. 5 shows the results. It is evident that the SSD between the two aligned gated images is smaller when using our proposed method than by the original demons algorithm in the same iteration number. That means the improved demons algorithm has a higher convergence rate than the original demons algorithm.

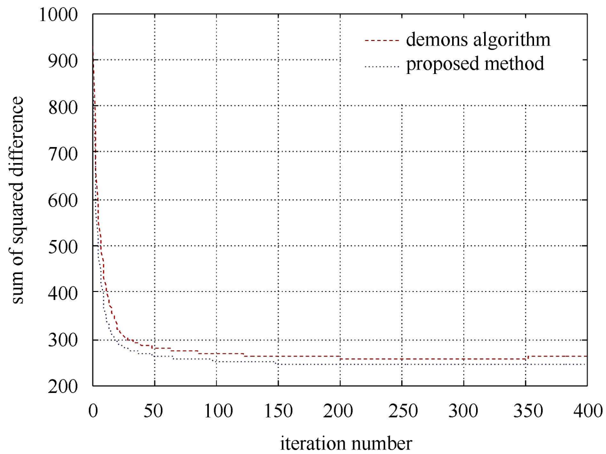

Fig. 5. SSD between the static image and the deformed moving image as a function of iteration number.

5 Conclusion

In this paper, the gated acquisition method is used to correct the motion effects in PET images. An improved demons algorithm is proposed to estimate the motion between the gated images. This method improves the convergence rate of the original demons algorithm and makes the registration results more accurate. The experimental results indicate that the spatial resolution of PET images has a significant improvement after motion correction, so the proposed method is superior to the original demons algorithm. Future work is needed to improve the image registration methods, for example, by proposing a better method for the discontinuity problem.

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