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Affine Motion Compensation with Improved Reconstruction in PROPELLER MRI

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***Abstract*—PROPELLER (Periodically Rotated Overlapping ParallEL Lines with Enhanced Reconstruction) MRI offers an effective means for compensating rigid motion during data collection. So far, this method has been evaluated clinically and found to be able to improve image quality through quantification and correction for head motion, where hypothetically only rotation and translation is present. During imaging of other parts of body, especially in abdomen, soft tissue such as liver, deformation occurs frequently. Traditional PROPELLER reconstruction can not model this kind of non-rigid body motion and can only attain limited compensation through correlation weighting. In this paper, a new method, named Affine PROPELLER, is proposed for affine motion correction, which extracts affine motion information from image space and compensates it in k-space. The experimental results show that the proposed method could correct artifacts due to not only the rigid motion but also the affine motion.**

***Index Terms*- MRI; PROPELLER; motion correction; affine transformation**

I. Introduction

MAGNETIC resonance imaging (MRI) is one of the most promising non-invasive diagnostic tools in current medicine. However, long data acquisition time makes MRI susceptible to patient motion. As a result, blurring and ghosting caused by patient motion may reduce anatomic details in MR images and limit the detection of pathological findings. In addition, motions such as heart-beating, respiration, blood flowing and wriggling of stomach or intestines are much severe obstacles for MRI.

PROPELLER MRI, proposed by J. G. Pipe in 1999 [1], offers a novel and effective means for compensating motion. This method segments the whole data acquisition into strips and there is an overlapped sampling area between strips. PROPELLER has the advantages of oversampling near the center of k-space and extracting motion information from the overlapped data between strips. The method has been evaluated clinically for quantification and correction for head motion and found to be able to reduce motion artifact and improve image quality in MR images [2]. Undersampling using asymmetric blades and taking advantage of Hermitian symmetries to fill-in the missing data significantly reduced imaging time without causing image artifacts[3]. Subsequently, a new concept named Turboprop is introduced[4], which employs an oscillating readout gradient during each spin echo of the echo train to collect more lines of data per echo train, which reduces the minimum scan time, motion-related artifact, and specific absorption rate (SAR) while increasing sampling efficiency. It can be applied to conventional fast spin-echo (FSE) imaging. TP-IDEAL was proposed to provide reliable water-fat separation with robust motion correction by combining Turboprop techniques and IDEAL (Iterative Decomposition of water and fat with Echo Asymmetry and Least-squares estimation)[5].

Many improved methods of PROPELLER MRI were proposed, but most of them can only be used to correct artifacts from rigid motion [6-8]. In MRI, we generally considered that the head motion is rigid, but in soft tissues imaging, such as liver, the motion may include resize or shear deformation besides rigid transformation. When non-rigid motion occurs, the traditional reconstruction algorithm for PROPELLER MRI can only attain limited compensation through correlation weighting. In this paper, a new method, named Affine PROPELLER, is proposed for affine motion correction in PROPELLER MRI, based on the theory that an affine transformation in image space corresponds to a determined affine transformation in k-space. The experimental results show that the proposed method could correct artifacts due to not only the rigid motion but also the affine motion.

II. Method

A. PROPELLER Data Collection

The k-space trajectory of PROPELLER data collection [9] is shown in Fig. 1. Data are collected along strips that rotate about the k-space center. Each strip consists of L lowest frequency phase encoded lines using any Cartesian sampling. Since each strip can be collected in a short time, the motion can be considered approximately only existing between the collections of strips. There is a circular region with a diameter of L/FOV near the k-space center which is sampled by every strip and the inter-strip motion can be extracted from data in this overlapped region.

Actually, data in the overlapped area can be seen as inherent "navigators". What's more, oversampling near k-space center can further help to reduce motion artifact.

Reconstruction of PROPLLER data involves phase correction, motion correction and gridding reconstruction [10]. Phase correction ensures that the point of rotation is the

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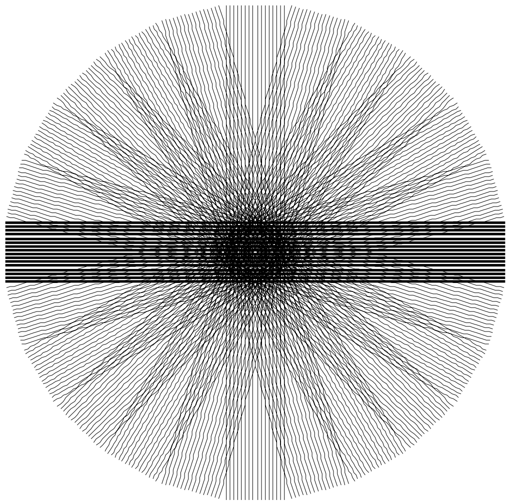

Fig. 1. Illustration of k-space sampling trajectory for PROPELLER MRI.

center of k-space. After inter-strip motion is estimated and onto Cartesian coordinates[11]. Finally, the inverse fast Fourier transform is performed to give the MR image.

B. Rigid Motion Artifacts Suppression

The algorithm for rigid motion estimation in PROPELLER MRI [10] is based on Fourier rotation and shift theorems: rotating an image in image domain is equivalent to rotating its Fourier transform by the same angle and translation in image domain causes some linear phase shifts in its Fourier transform, they are expressed as follows.

$$\Im(f(r,\theta+\Delta\theta)) = F(k,\phi+\Delta\theta)\,, \quad (1)$$

where $f(r,\theta)$ and $F(k,\phi)$ is respectively the polar coordinate form of $f(x,y)$ and $F(u,v)$, $\Delta\theta$ is the rotation angle of images.

If rotating is occurred in the process of data collection, in order to suppress the rotation artifacts, we must find the angle $\Delta\theta$, and rotate the k-space data by same angle but inverse direction.

$$\Im(f(x-\Delta x, y-\Delta y)) = F(u,v)e^{-j2\pi(\frac{u\Delta x}{M}+\frac{v\Delta y}{N})}, \quad (2)$$

where $f(x,y)$ is image data, $F(u,v)$ is the Fourier transform of $f(x,y)$. Δx and Δy is respectively the translation in the *x* and *y* directions. *M* and *N* is respectively the length and width of image.

If translation is occurred in the process of data collection, in order to suppress the translation artifacts, we must find the translation parameters (Δx , Δy) and eliminate the phase shift $e^{-j2\pi(\frac{u\Delta x}{M}+\frac{v\Delta y}{N})}$ in the k-space data.

The translation (Δx , Δy) and rotation $\Delta\theta$ can be found by DART registration algorithm [12].

C. Affine Motion Artifacts correction

An affine transformation is composed of linear transformations (rotation, scaling or shear) and a translation. Geometric contraction, expansion, dilation, reflection, rotation, shear, similarity transformations, spiral similarities, and translation are all affine transformations, as are their combinations. Its representation is written in matrix form as

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (3)$$

where *a* and *e* are the scaling coefficients, *b* and *d* is respectively the shear coefficient along *x* direction and *y* direction, *c* and *f* are translation coefficients.

If $\begin{bmatrix} a & b \\ d & e \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$, equation (3) can be rewritten as

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & c \\ \sin\theta & \cos\theta & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (4)$$

Actually, equation (4) represents a rigid transformation, so we can suggest that rigid transformation is a particular example of affine transformation.

Given the image $f(x,y)$, then the Fourier transform of $f(ax+by+c, dx+ey+f)$,which is the affine transformation of $f(x,y)$, can be written as

$$\Im(f(ax+by+c, dx+ey+f)) = \frac{1}{|\Delta|} e^{\frac{j2\pi}{\Delta}[(ec-bf)u+(af-cd)v]} F(\frac{e}{\Delta}u - \frac{d}{\Delta}v, \frac{-b}{\Delta}u + \frac{a}{\Delta}v) \quad (5)$$

where $\Delta = \begin{vmatrix} a & b \\ d & e \end{vmatrix} = ae - bd$. In view of (5), it is obvious that $F(\frac{e}{\Delta}u - \frac{d}{\Delta}v, \frac{-b}{\Delta}u + \frac{a}{\Delta}v)$ is the affine transformation of $F(u,v)$, which means that an affine transformation in the image domain is equivalent to an affine transformation for its Fourier transform.

In the ideal condition, the measured MR data is $F(u,v)$. However, when the affine movement with parameters (*a,b,c,d,e,f*) occurred, the data we collected actually are $\frac{1}{|\Delta|} e^{\frac{j2\pi}{\Delta}[(ec-bf)u+(af-cd)v]} F(\frac{e}{\Delta}u - \frac{d}{\Delta}v, \frac{-b}{\Delta}u + \frac{a}{\Delta}v)$, which is an affine transformation of $F(u,v)$. In order to suppress the affine motion artifacts, we must find the parameters *a*, *b*, *c*, *d*, *e* and *f*, and correct the collected data by those parameters.

A temp image can be reconstructed by using each single strip and padding the rest of the k-space with zeros. Therefore, it is possible to extract motion information from these temp images. Firstly, we set the first temp image to be the reference image, then we estimate the affine coefficients of all the temp images compared with the reference image by image registration. The formula of parameter estimation can be written as

$$M_i = \arg\min \Phi(M_i) \quad (6)$$

$$\Phi(M_i) = \sum (M_i \bullet I_i - I_0)^2 \quad (7)$$

where I_0 is the magnitude of the reference image, which is reconstructed from the first k-space strip. I_i is the magnitude of the floating image, which is reconstructed from the i^{th} k-space strip. M_i is the affine coefficients of the i^{th} k-space strip, namely $M_i = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix}$. $M_i \bullet I_i$ represents the affine transformation of the i^{th} temp image, whose coefficients is M_i. $i = 1, \cdots, h$, h is the number of k-space strips.

In summary, the main steps of the proposed method are:

1) Get the temp images by using each single strip and padding the rest of the k-space with zeros.
2) Estimate the affine parameters between the temp images according to equation (6) and (7).
3) Correct all the k-space strips by the affine parameters which are estimated in step 2).
4) Combine the k-space strips and perform gridding reconstruction[11].

III. Results

In this paper, the data are simulated from image of Standent template with 18 strips, 24 phase-encoded lines in each strip and 256 sampled data in each phase-encoded line. Two groups of experiments were carried out, the first was added rigid motion artifacts and another was added affine motion artifacts (we added the motion artifacts into the 5^{th},6^{th},7^{th},8^{th},9^{th},14^{th},15^{th} and 16^{th} strips, the size of those rigid parameters (Δx , Δy $\Delta\theta$) and affine parameters (*a, b, c, d, e, f*) are show in TABLE I).

The algorithm for rigid motion estimation in Ref. [7] can correct the rigid motion artifacts reliably and accurately, so we compared it with the proposed method. In order to depict expediently, we call it Rigid PROPELLER, and call the proposed method Affine PROPELLER accordingly.

TABLE I
The motion parameters which we added into the k-space strips

strip	5	6	7	8
$\Delta x,\Delta y,\Delta\theta$ rigid motion	0,0,0	-0.2528, 0.3528,3.6	-0.2045, 0.3045,3.75	0.3627, 0.2627,3.46
a,b,c,d,e,f affine motion	0.092,0.039 , 0,-0.036, 0.958,0	0.968,0.042, -0.3528,-0.04 2,0.962,0.253	0.957,0.031, -0.3045,-0.03 5,0.965,0.205	0.964,0.041, 0.2627,-0.045 ,0.956,0.3627
strip	9	14	15	16
$\Delta x,\Delta y,\Delta\theta$ rigid motion	0.3775,-0.4 084,3	0.2546,-0.577 5,2.86	0.3794,-0.379 4,3.16	0.2658,-0.486 5,3.25
a,b,c,d,e,f affine motion	0.956,0.034 , 0,-0.045, 0.963,0	0.963,0.042, 0.4775,-0.041 , 0.964,-0178	0.958,0.0382, 0.1546,-0.039 , 0.956,-0.558	0.962,0.037, 0.3794,-0.043 , 0.963,-0.379

Fig. 2 represents a comparison of the results of rigid motion artifacts suppression. Fig. 2 (a) is the original image, Fig. 2 (b) is reconstructed without correction, Fig. 2 (c) is reconstructed by Rigid PROPELLER, Fig.2(d) is reconstructed by Affine PROPELLER. It can be seen that the results of two methods have little difference in visual sensation, and both of them can correct rigid motion artifacts efficiently. Fig. 3 is the profiles of Fig. 2 (a),(c) and (d) on 128^{th} line, which shows that the profiles of two methods are almost coincident. TABLE II gives the NMSE (Normalized Mean Square Error, whose formula is given as follows) of images reconstructed by the two methods. It displays that the NMSE of two methods are very close.

$$NMSE = \frac{\sum |I - I_0|^2}{\sum |I_0|^2} \tag{8}$$

where I_0 is the orignal image, I is the reconstructed image.

TABLE II
A comparison of the NMSE of two methods

	Rigid PROPELLER	Affine PROPELLER
NMSE	0.019844	0.020442

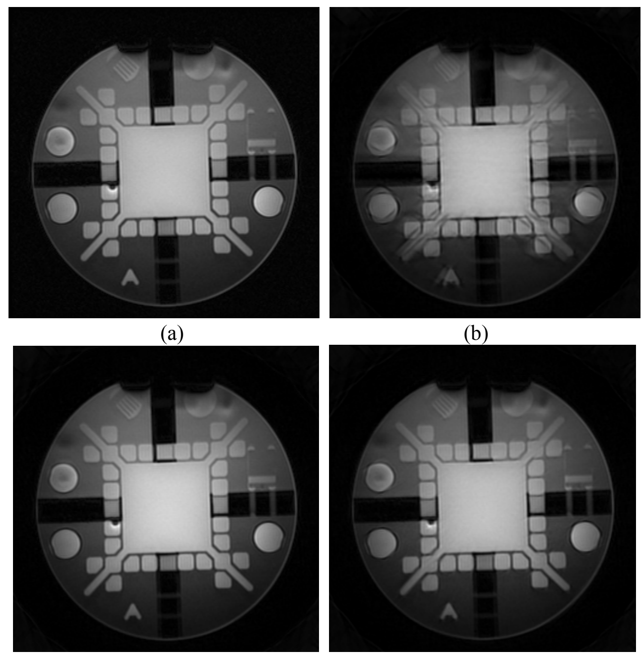

Fig. 2. A comparison of the results of rigid motion artifacts suppression. (a) is the orignal image and (b) is reconstructed without correction. (c) is reconstructed by Rigid PROPELLER and (d) is reconstructed by Affine PROPELLER.

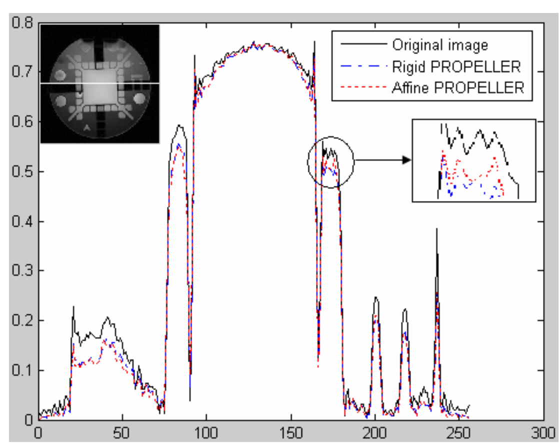

Fig. 3. Profiles of Fig. 2 (a),(c) and (d) on 128^{th} line.

Fig. 4 represents a comparison of the results of affine motion artifacts suppression. Fig. 4 (a) is the original image, Fig. 4 (b) is reconstructed without correction, Fig. 4 (c) is reconstructed by Rigid PROPELLER, Fig.4(d) is reconstructed by Affine PROPELLER. It can be see that the result of Affine PROPELLER is better than that of Rigid PROPELLER in visual sensation. Affine PROPELLER can correct the affine motion artifacts while Rigid PROPELLER can't. Fig. 5 is the profiles of Fig. 4 (a), (c) and (d) on 128th line, from which we can know that the profile of Affine PROPELLER is closer to original image's than that of Rigid PROPELLER. TABLE III gives the NMSE of two methods. It displays that the NMSE of Rigid PROPELLER is bigger than that of Affine PROPELLER.

TABLE III
A Comparison of the NMSE of two methods

	Rigid PROPELLER	Affine PROPELLER
NMSE	0.023217	0.013066

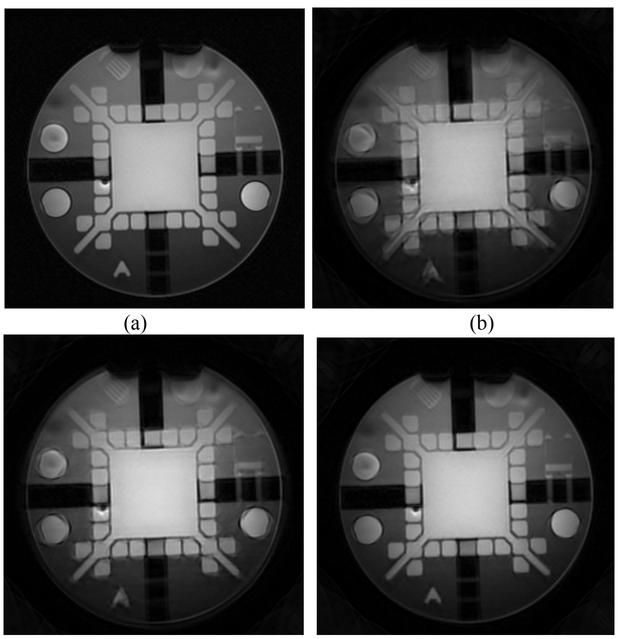

Fig. 4. A comparison of the results of affine motion artifacts suppression. (a) is the orignal image and (b) is reconstructed without correction. (c) is reconstructed by Rigid PROPELLER and (d) is reconstructed by Affine PROPELLER.

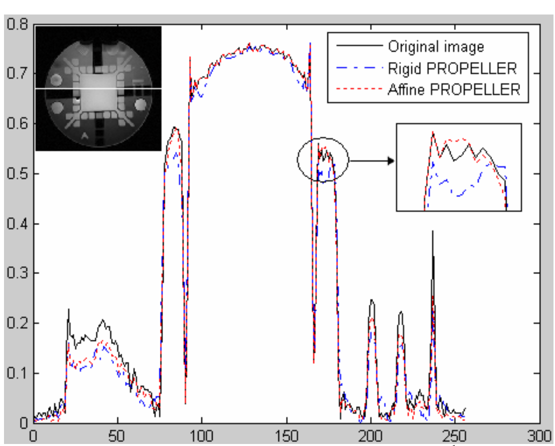

Fig. 5. Profiles of Fig. 4 (a),(c) and (d) on 128th line.

IV. CONCLUTION

In this paper, a new method based on affine transformation is proposed for suppressing motion artifacts, which can correct both rigid motion artifacts and affine motion artifacts efficiently. It is of potential use for correcting the motion artifacts of the soft tissues in MRI. In addition, the simulated experiment have been finished, and the real data experiment will be carried out in the next step.

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