Phase contrast (PC) MR image reconstruction using complex expectation maximization (EM)

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Introduction

In MRI, radial sampling can be more efficient than the Cartesian sampling in certain applications such as angiography. The highly-constrained projection reconstruction (HYPR)-based algorithms provided high spatio-temporal images by using the composite information [1, 2]. The HYPR method is an identical method to expectation maximization (EM) method, which is widely used in positron emission tomography (PET). However, the fact that HYPR can reconstruct magnitude images only is a critical limitation for MR applications, such as phase contrast (PC) imaging, which needs phase information. To overcome this limitation, the complex HYPR local reconstruction (LR) method was proposed [3]. In the complex HYPR-LR method, the subsampling artifact in the phase information is removed by using a subsampled synthesized composite image. While the technique shows efficient performance, artifacts might not be successfully removed if the coherence between the composite image and the target image is not guaranteed. In this study, we propose a new reconstruction method of complex image for dynamic PC imaging based on EM algorithm.

Methods

In the EM algorithm or HYPR based algorithm, iterative reconstruction formula is described as follows:

$$I^{k+1} = I^k \boldsymbol{R}^{-1}\left(\frac{S}{\boldsymbol{R}(I^k)}\right), \text{ for } k = 1, 2, \cdots K \qquad (1)$$

where S is undersampled sinogram data with a reduced number of views. $\boldsymbol{R}$ denotes Radon transform or projection operator and $\boldsymbol{R}^{-1}$ is its adjoint operator which is the non-filtered back-projection. I^k is the result image of the k-th iteration and the composite image, I^1, is used as an initial image for iteration. The iteration formula described above, however, can only reconstruct magnitude images, which have positive-real values only. To adopt the algorithm for PC imaging, complex-valued image should be reconstructed. In this study, we separated the complex sinogram data into real and imaginary parts, and reconstructed each part (real and imaginary) using the inequality constraints [4]. By assuming that the image (I) has bounded pixel values between L and U, then real and imaginary parts of the difference (I-L) can be acquired from the above-mentioned algorithm because real(I-L) and imag(I-L) always have positive values. Similarly, real and imaginary parts of (U-I) can be also reconstructed. In that case, S should be replaced with S-$\boldsymbol{R}(L)$ and $\boldsymbol{R}(U)$-S in Eq. (1). Those two intermediate complex images, which are described as $I^{L,k+1}$ and $I^{U,k+1}$, are combined, thereby generating I^{k+1} as follows:

$$I^{k+1} = \frac{I^{L,k+1}U + I^{U,k+1}L}{I^{L,k+1} + I^{U,k+1}} \qquad (2)$$

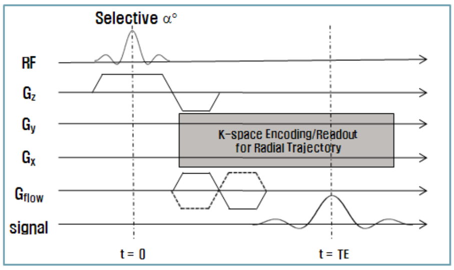

Figure 1. Phase contrast (PC) sequence with radial trajectory

Results

To demonstrate the performance of the proposed method, a homemade flow phantom was used. The flow phantom consisted of a water bottle and a tube having an inner diameter of 12mm, through which water flowed constantly. For PC imaging, a gradient-echo sequence with flow encoding gradients (velocity-encoding value (venc) = 150cm/s) was applied to the through-plane direction (Fig. 1) using the following parameters: TR/TE/flip angle/FOV/slice thk = 10 ms/5 ms/15°/300 mm^2/5 mm. For experiment, we totally acquired 25 PC images, each of which was reconstructed from 256 projection views and had different flow speed. After acquisition, we subsampled the acquired data with reduction factor 8 (32 projection views for each flow spead) and reconstructed the images from the subsampled projection views using the filtered back-projection (FBP), the complex HYPR LR and the proposed method. For comparison, magnitude images were reconstructed and magnitude-masked phase difference images were obtained as shown in Fig. 2. The magnitude-masked phase difference image can be obtained by multiplying the magnitude image and phase difference image. As shown in Fig. 2(a), both the complex HYPR LR and the proposed methods provided magnitude images with superior quality than the FBP method. However, Fig. 2(b) shows that the proposed method could remove the subsampling artifacts in the phase information more efficiently than the HYPR-LR or the FBP methods. In addition, estimated flow speed was analyzed using correlation analysis and Bland-Altman analysis as plotted in Fig. 3. Fig. 3 shows that the proposed method generates more accurate flow velocity than other methods.

Conclusions

In this study, we proposed a novel reconstruction technique for complex-valued images. We demonstrated the performance of the proposed method using PC imaging. In the flow phantom experiments, the proposed method was used to reconstruct magnitude and magnitude-masked phase difference images and was compared with other reconstruction algorithms. Further analysis was performed using linear regression and Bland-Altman plot. As shown in the experiments, the proposed method can efficiently remove the streaking artifacts, while successfully estimating the flow velocity.

References

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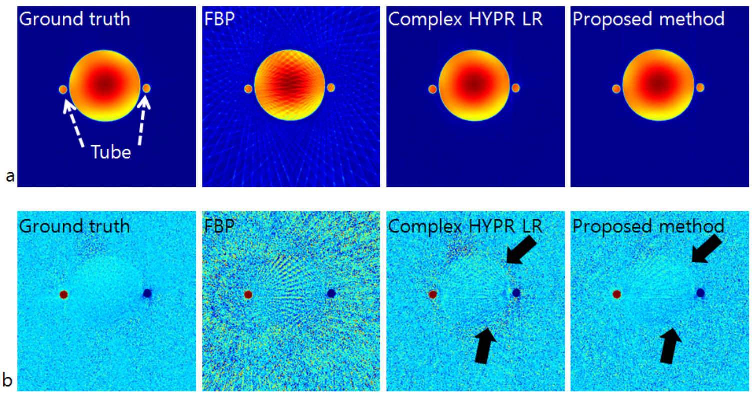

Figure 2. Magnitude and magnitude-masked phase difference images of flow phantom study. The first column is the ground truth images reconstructed by FBP from 256 projection views, the second column images were reconstructed by FBP from 32 projection views. The third and fourth column images were reconstructed by the complex HYPR LR and the proposed method from 32 projection views, respectively. (a) Magnitude images, (b) magnitude-masked phase difference images.

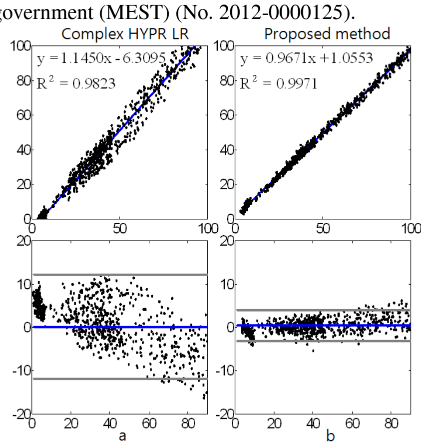

Figure 3. Regression and Bland-Altman plots of the estimated flow velocity of the flow phantom using (a) complex HYPR LR and (b) the proposed method