caipirinha using the RF pulse modulation with random phase for multiband imaging

Changheun Oh[1], Dongchan Kim[2], and HyunWook Park[2]

[1]Korea advanced institute of science and technology, Daejeon, Daejeon, Korea, [2]Korea advanced institute of science and technology, Daejeon, Korea

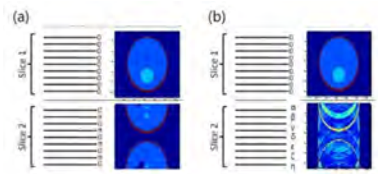
Introduction : Reducing the imaging time is one of the most important issues in MRI. Multi-band imaging and parallel imaging techniques are the solutions for reducing the imaging time as these techniques can reconstruct images from sub-sampled MR data. In multi-band imaging technique, CAIPIRINHA well reconstructs multi slices by modulating the phase of RF pulses[1]. But imaging regions that have similar sensitivity value in multi-channel RF coils have high g-factor, thereby degrading SNR of the reconstructed image[2]. In this work, we propose a new multi-band imaging technique by using the RF pulse modulation with random phase to make uncorrelated aliasing pattern.

Methods : To make the controlled aliasing for multi-band imaging, CAIPRINHA modulates the phase of RF pulse so that individual slice can be shifted in phase encoding (PE) direction. The shift of individual slice enhances the difference of spatial sensitivity in PE direction for reconstructing the aliased images. But for high acceleration factor (AF), shift of individual slice in CAIPIRINHA is not enough to reconstruct multi-slice images without aliasing artifacts. We make the RF pulse modulated with random phases which could make uncorrelated aliasing pattern as shown in Figs. 1 (a) and (b). The phase increasing by Golden Ratio guarantees the uniform distribution for any arbitrary number of phases, especially when the number of phases being a Fibonacci number. The phase of RF pulse increasing by Golden Ratio is generated as follows[3]:

$$\phi(n) = n \cdot 111.25^\circ \quad 1 \le n \le N_y \qquad (1)$$

where N_y is the total number of PE lines. To make the uniformly distributed aliasing pattern, we first generated RF phase sets with Fibonacci numbers (P_n) as follows:

$$\begin{aligned} S_1 &= \{\phi(1), \ldots \phi(P_1)\} \\ S_2 &= \{\phi(P_1+1), \ldots \phi(P_2)\} \\ &\vdots \\ S_{N-1} &= \{\phi(P_{N-2}+1), \ldots \phi(P_{N-1})\} \\ S_N &= \{\phi(P_{N-1}+1), \ldots \phi(N_y)\}, \quad \textit{for} \quad P_{N-1} < N_y \le P_N \end{aligned} \qquad (2)$$



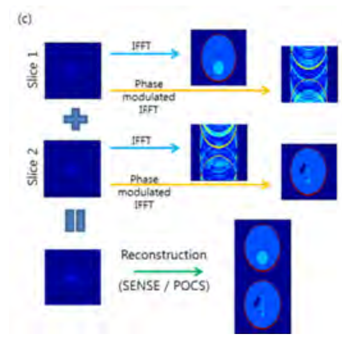


Figure 1. The RF phase modulation to make controlled aliasing in (a) the conventional CAIPIRINHA and (b) the proposed random CAIPIRINHA. (c): Reconstruction of single slice data with phase modulated IFFT and multiband data with SENSE and POCS.

where P_i is the ith Fibonacci number. By the property of Golden Ratio, each phase set, from $\mathbf{S}_1$ to $\mathbf{S}_N$, has uniform phase distribution. In addition, PE lines are segmented with the Fibonacci number as follows:

$$\begin{aligned} PE_1 &= \left\{ |k_y| \le \frac{P_1}{2} \right\} \\ PE_2 &= \left\{ \frac{P_1}{2} < |k_y| \le \frac{P_2}{2} \right\} \\ &\vdots \\ PE_{N-1} &= \left\{ \frac{P_{N-2}}{2} < |k_y| \le \frac{P_{N-1}}{2} \right\} \\ PE_N &= \left\{ \frac{P_{N-1}}{2} < |k_y| \le \frac{N_y}{2} \right\} \end{aligned} \qquad (3)$$

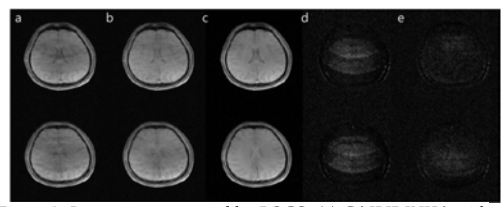


Figure 2. Images reconstructed by POCS; (a) CAIPIRINHA with alternating phase, (b) proposed method. (c): fully sampled reference image. (d): Difference between the reference image and CAIPIRINHA. (e): Difference between the reference image and the proposed method.

Then, each phase in a phase set $\mathbf{S}_i$ is randomly reordered and used for the phase of RF pulse of each PE line in $\mathbf{PE}_i$.

In the proposed method, multi-slices are excited where each slice has different phase from the other slices and the phase is randomly distributed in PE. Therefore, aliasing pattern of other slices can be shown as random noise in a reconstructed image. Thus, Compressed Sensing (CS) can be proper to eliminate the noise-like errors. CS reconstruction is conducted as the following equation:

$$\underset{I}{\text{argmin}} \; \|F_u I - y\|_2^2 + \lambda \|\Psi I\|_1 \qquad (4)$$

where F_u is under-sampled Fourier Transform with random RF phase modulation, I is the reconstructed images, y is the sampled k-space data, λ is the data consistency tuning constant and Ψ is the sparsifying transform. Eq. (4) is solved with iterative POCS techinique[4]. For *in-vivo* experiment, we used the modified FLASH sequence with 12 channel head array coil in 3T MRI system (SIEMENS Verio, Germany) and T1 weighted images were acquired with following parameters; TR/TE = 250/3.1 ms, FOV = 220 × 220 mm, matrix size = 256 × 256, slice thickness = 5 mm, gap between slices = 1 mm.

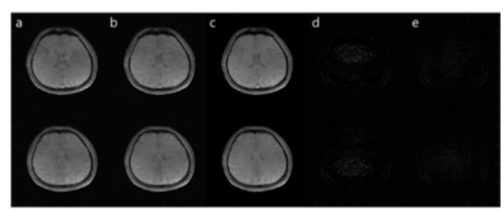


Figure 3. Images reconstructed by POCS; (a) CAIPIRINHA with alternating phase, (b) proposed method. (c): fully sampled reference image. (d): Difference between the reference image and CAIPIRINHA. (e): Difference between the reference image and the proposed method.

Results : To show the performance of the proposed method, experiments with several pairs of multi-band AF (R_{MB}) and parallel imaging AF (R_{PI}) were performed by retrospectively sub-sampling the fully sampled *in-vivo* dataset. Fig. 2 shows images reconstructed by SENSE technique and difference between the reconstructed images and the fully-sampled reference image. As shown in Fig. 2, the proposed method shows better performance than CAIPIRINHA with AF of $R_{MB} \times R_{PI} = 2 \times 3$. Nevertheless, as shown in Figs. 2 (d) and (e), artifacts are still shown in both methods. To improve the quality of the reconstructed images, iterative reconstruction was performed with POCS technique. Fig. 3 shows the results of POCS reconstruction. Regions with high g-factors in conventional CAIPIRINHA have vigorous noise as shown in Fig. 2 (d) and Fig. 3 (d). In contrast, reconstructed image from the proposed method shows uniformly distributed noise as shown in Fig. 2 (e) and the uniformly distributed noise of the proposed method was well reduced by POCS reconstruction as shown in Fig. 3 (e).

Conclusions : In this work, we proposed a new randomized RF phase based multi-band imaging technique which could reduce reconstruction noise by CS-based reconstruction technique. As shown in our experiment results, the proposed method showed better performance than CAIPIRINHA, especially for large AFs.

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